# Present day $CO_2$ cycle in the coastal ocean and possible evolution under global change

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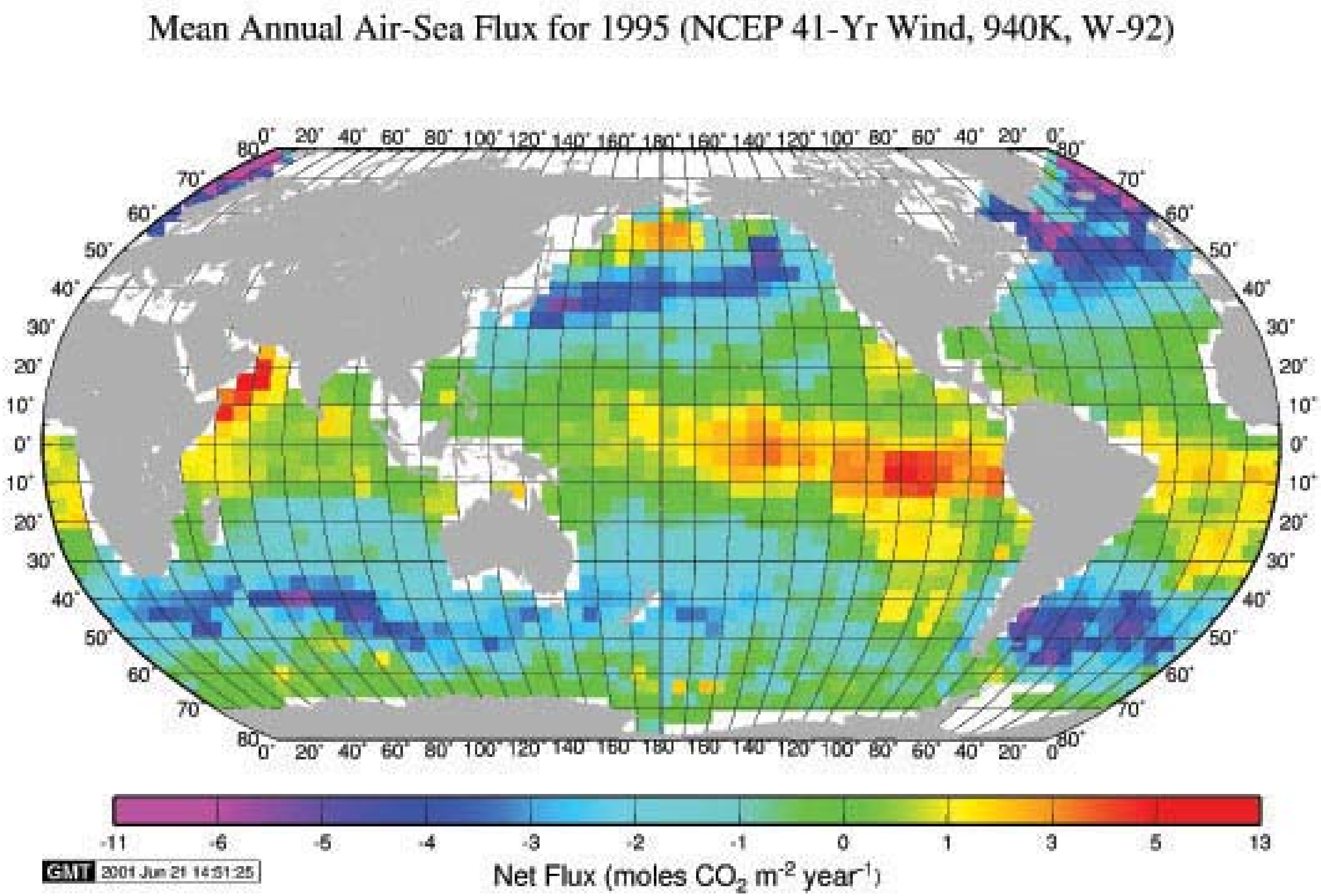
# Present day $CO_2$ cycle in the coastal ocean

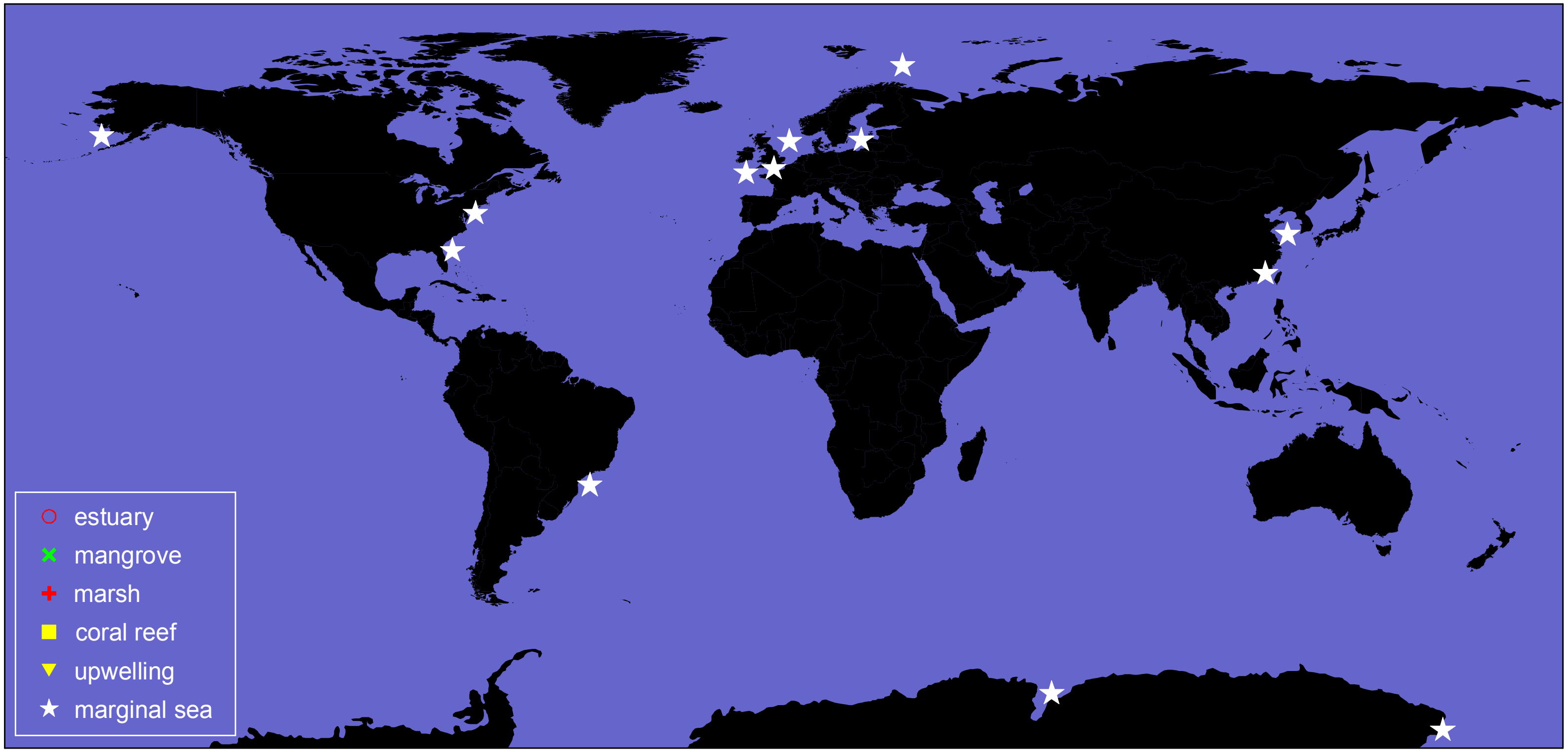
# Issue




Takahashi, T. et al. (2002). Deep-Sea Res. II, 1601-1622.

**What would happen if we tried to fill the white pixels ?**

# Marginal seas (Fluxes in mol C $m^{-2}$ $yr^{-1}$)

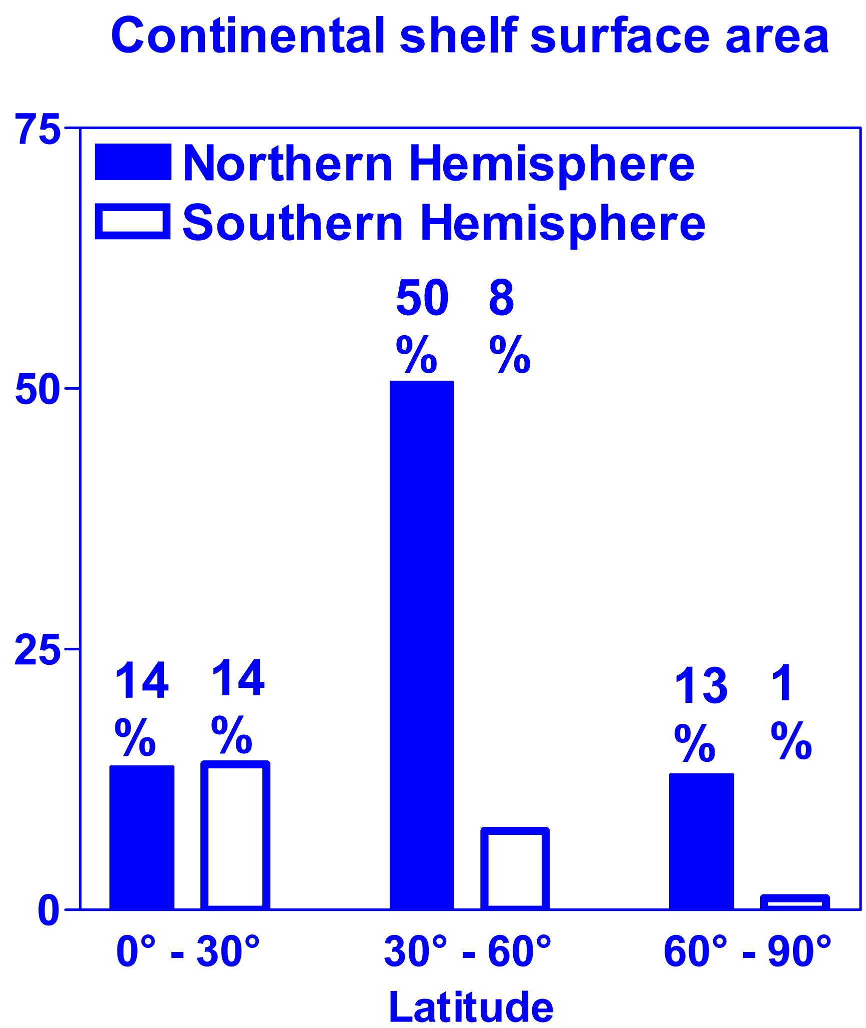



| High latitude: | | Temperate latitudes: | | Sub-tropical & tropical latitudes: | |
|---|---|---|---|---|---|
| Barents Sea | -3.6 | Baltic Sea | -0.8 | US South Atlantic Bight | +2.5 |
| Bristol Bay | -0.2 | North Sea | -1.4 | South China Sea | +1.8 |
| Pryzd Bay | -2.2 | English Channel | 0.0 | Southwest Brazilian coast | +1.3 |
| Ross Sea | -1.8 | Gulf of Biscay | -2.9 | | |
| | | US Middle Atlantic Bight | -1.2 | | |
| | | East China Sea | -2.1 | | |

## Latitudinal variability in $CO_2$ fluxes counts !

Borges (2005) Estuaries 28(1), 3-27

# Marginal seas




**Latitudinal variability in surface area also counts !**

Borges (2005) Estuaries 28(1), 3-27

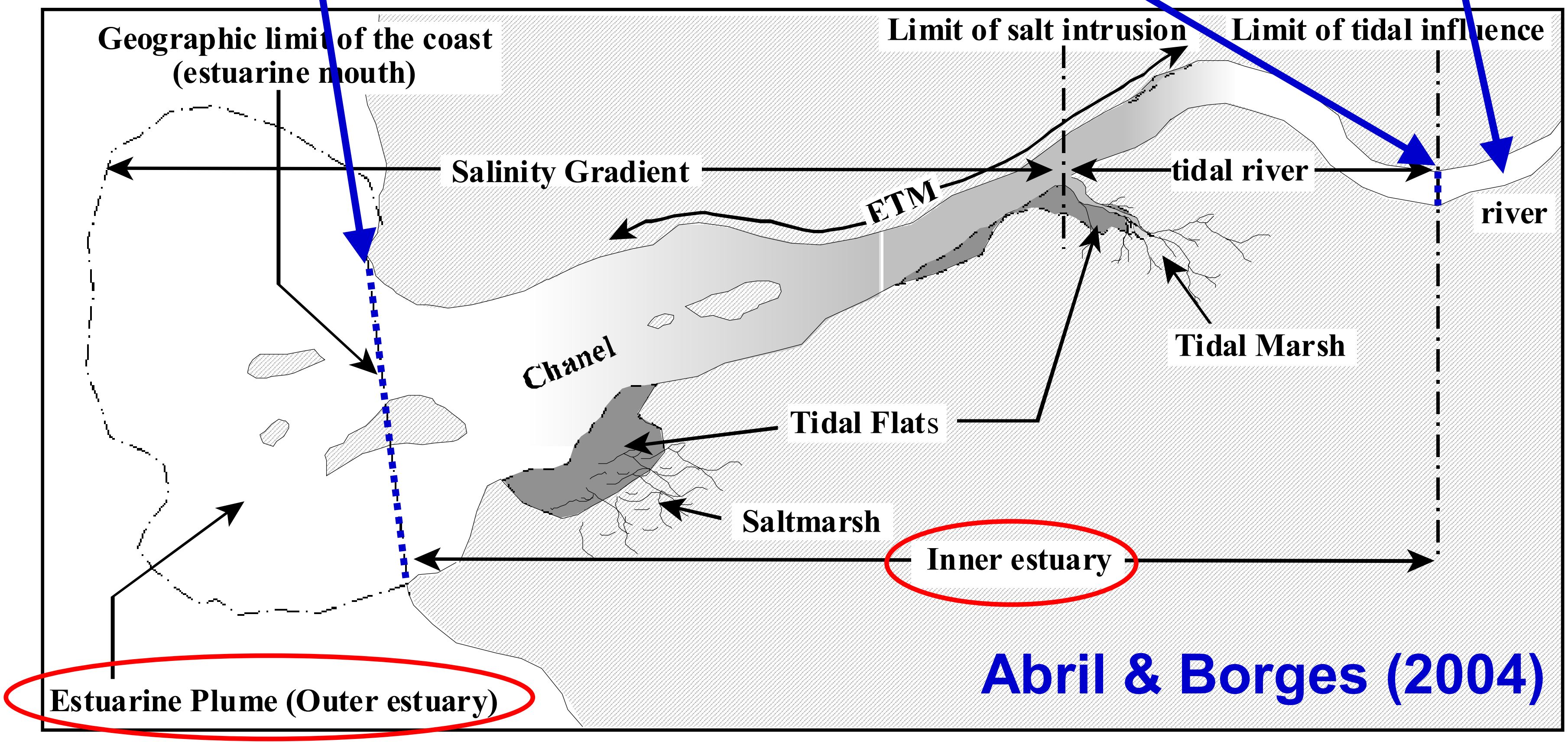
# Estuaries

## Where does the coastal ocean start ?

Arthur Chen

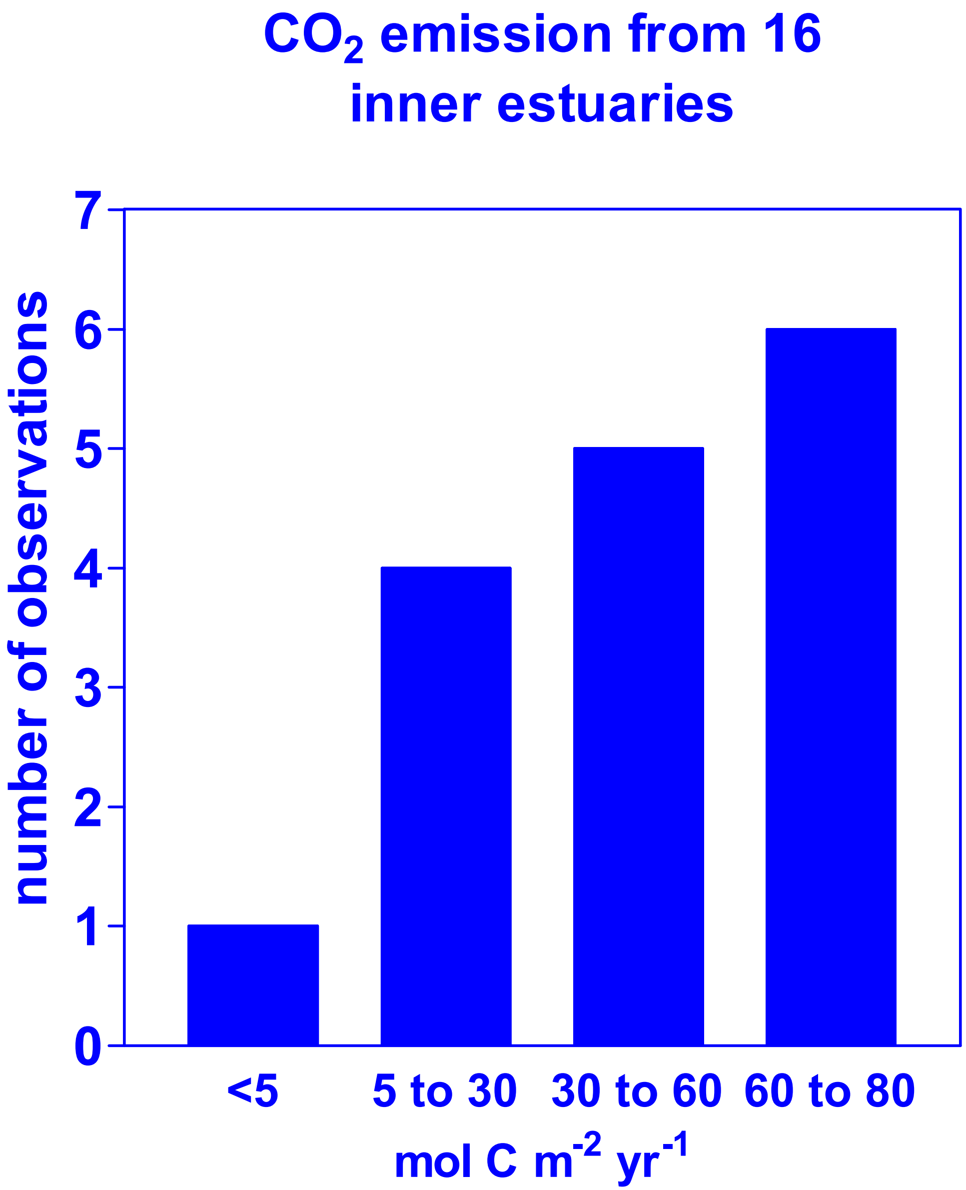
Alberto Borges

C,N & P inputs by Kempe, Meybeck, Ludwig, etc…




Abril & Borges (2004)

# Estuaries (Fluxes in mol C $m^{-2}$ $yr^{-1}$)




**Temperate estuaries (12)**
**46 mol C $m^{-2}$ $yr^{-1}$**

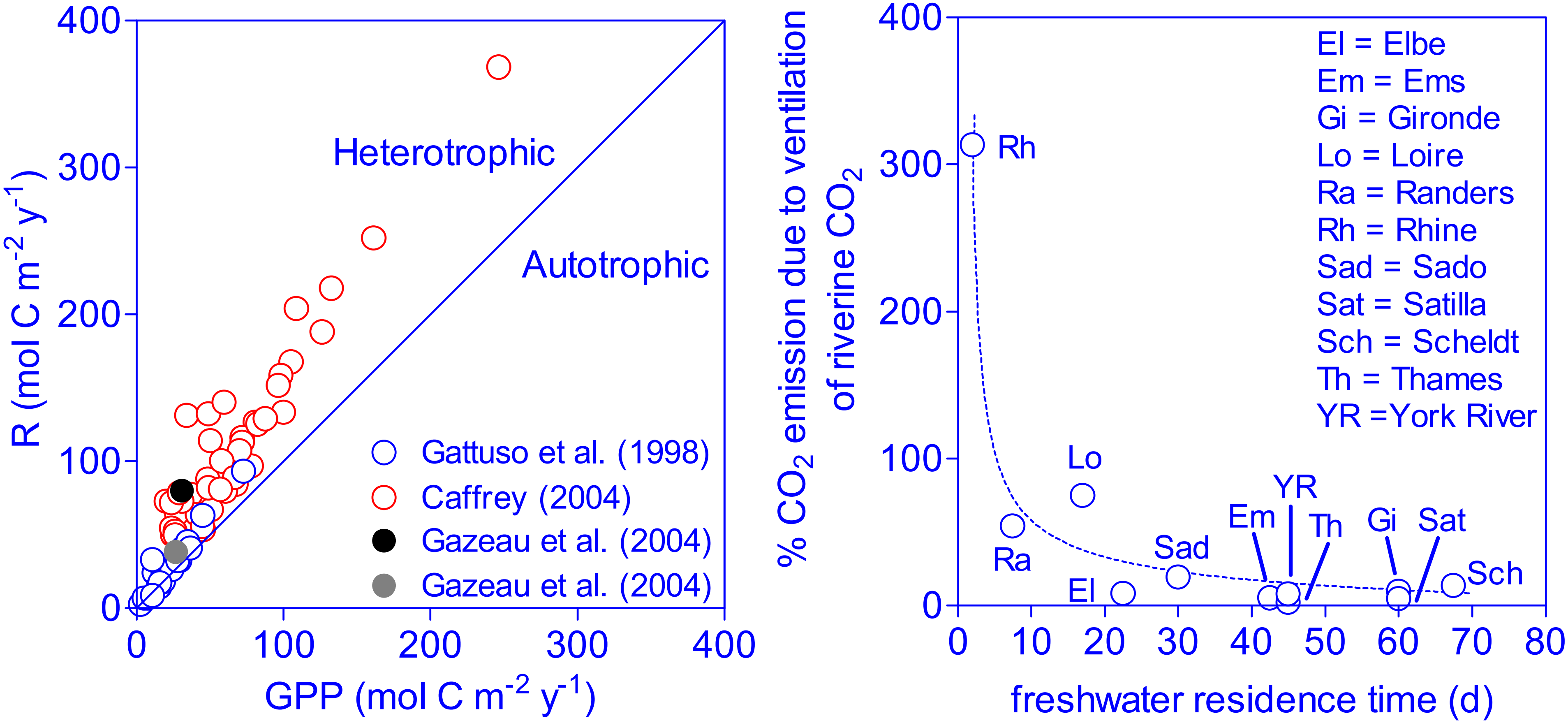
**Tropical estuaries (4)**
**19 mol C $m^{-2}$ $yr^{-1}$**

**High latitude estuaries ?**

**Borges (2005) Estuaries 28(1), 3-27**

# Estuaries

**Net Ecosystem Production NEP = GPP – R**
**<NEP> = - 32.4 molC $m^{-2}$ $yr^{-1}$ (n=65) = strongly heterotrophic**
**Riverine $CO_2$ input = 10% of total $CO_2$ emission**




**Borges et al. (2006) ECSS 70(3), 375-387**

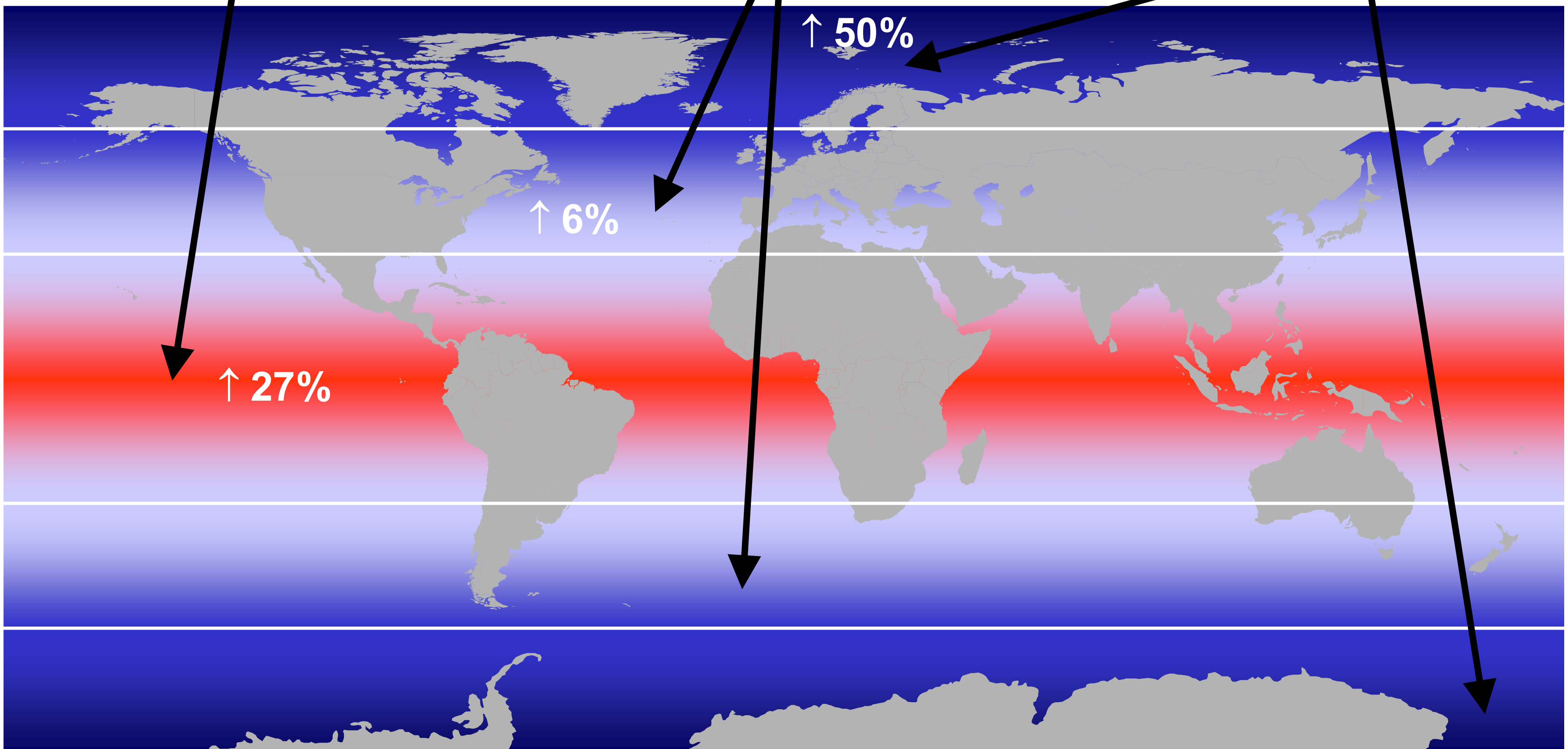
# Up-scaling

Coastal -0.05 Pg C $y^{-1}$ Open -1.57 Pg C $y^{-1}$ Global -1.61 Pg C $y^{-1}$ ↑ 3%

| | |
|---|---|
| Coastal | +0.18 Pg C $y^{-1}$ |
| Open | +0.71 Pg C $y^{-1}$ |
| Global | +0.90 Pg C $y^{-1}$ |

| | |
|---|---|
| Coastal | -0.13 Pg C $y^{-1}$ |
| Open | -2.06 Pg C $y^{-1}$ |
| Global | -2.19 Pg C $y^{-1}$ |

| | |
|---|---|
| Coastal | -0.10 Pg C $y^{-1}$ |
| Open | -0.22 Pg C $y^{-1}$ |
| Global | -0.33 Pg C $y^{-1}$ |



# Up-scaling : ecosystem diversity counts !

Overall coastal ocean small $CO_2$ sink (−0.05 PgC $yr^{-1}$)

Marginal seas strong sink (−0.45 PgC $yr^{-1}$)

Near-shore systems (estuaries, mangroves, marshes, coral reefs, upwelling systems) strong sources (+0.40 PgC $yr^{-1}$)

Borges (2005) Estuaries 28(1), 3-27

# Up-scaling : ecosystem diversity counts !

| | $PgC\ yr^{-1}$ | % total |
|---|---|---|
| Estuaries | 0.324 | 81.1 |
| Marsh waters | 0.036 | 9.0 |
| Mangroves waters | 0.033 | 8.2 |
| Coral reefs | 0.005 | 1.3 |
| Upwelling | 0.002 | 0.5 |
| | | |
| Nearshore systems | 0.400 | 100 |

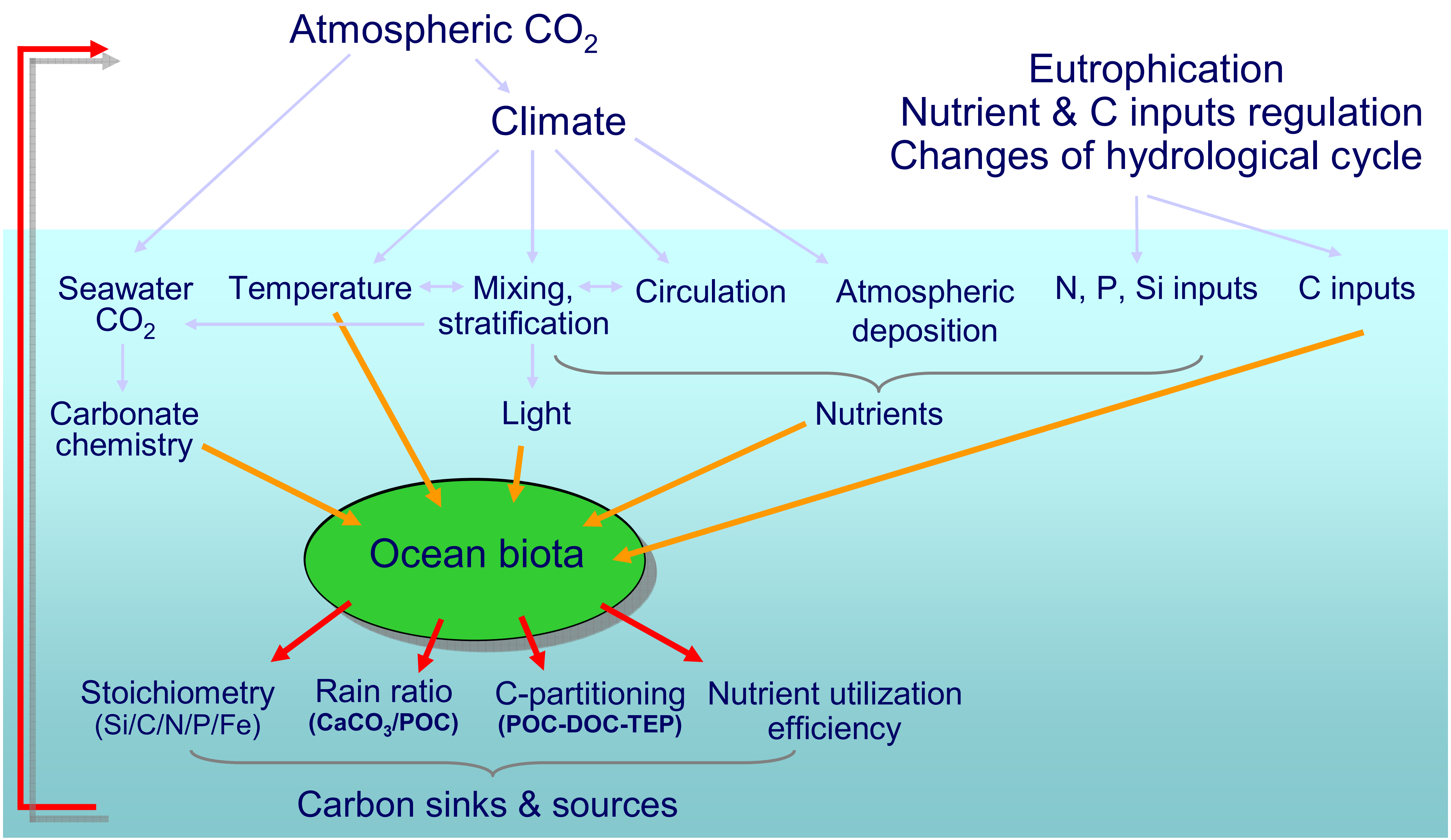
These are also the most vulnerable ecosystems to human pressure !

Strong feedbacks on increasing atmospheric $CO_2$ ?

Borges (2005) Estuaries 28(1), 3-27

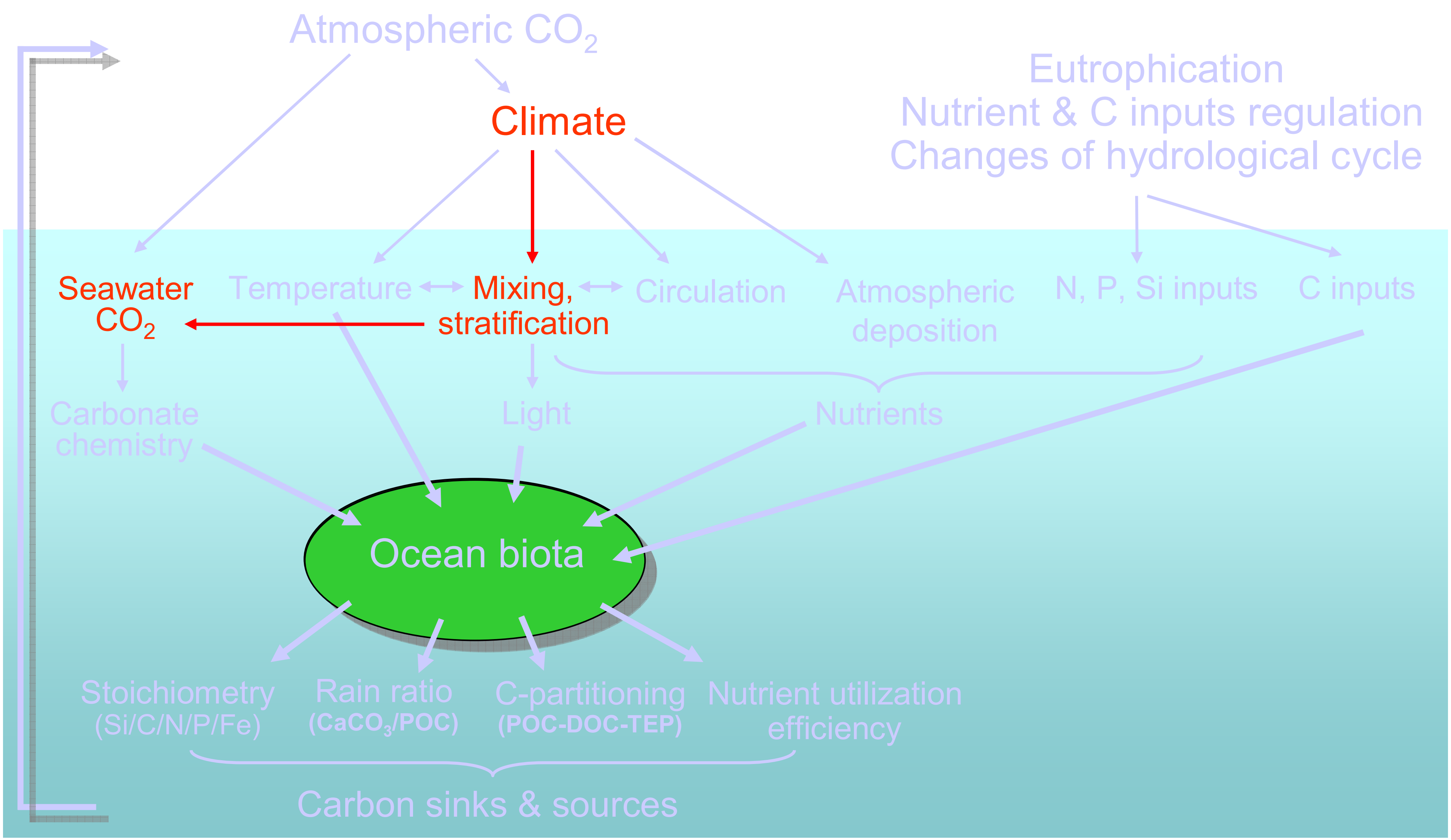
# Possible evolution under global change

# Multiple divers and responses

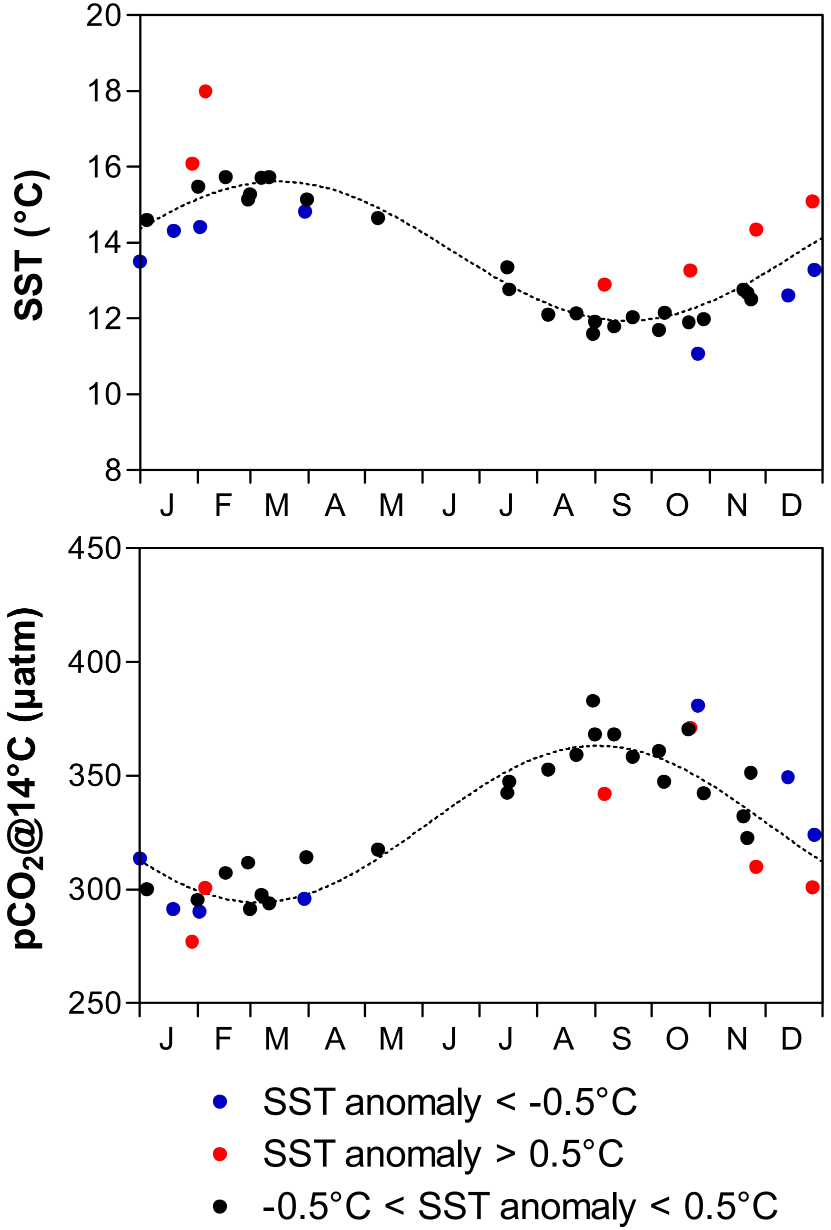



**Modified from Riebesell (2007) SOVOC meeting**

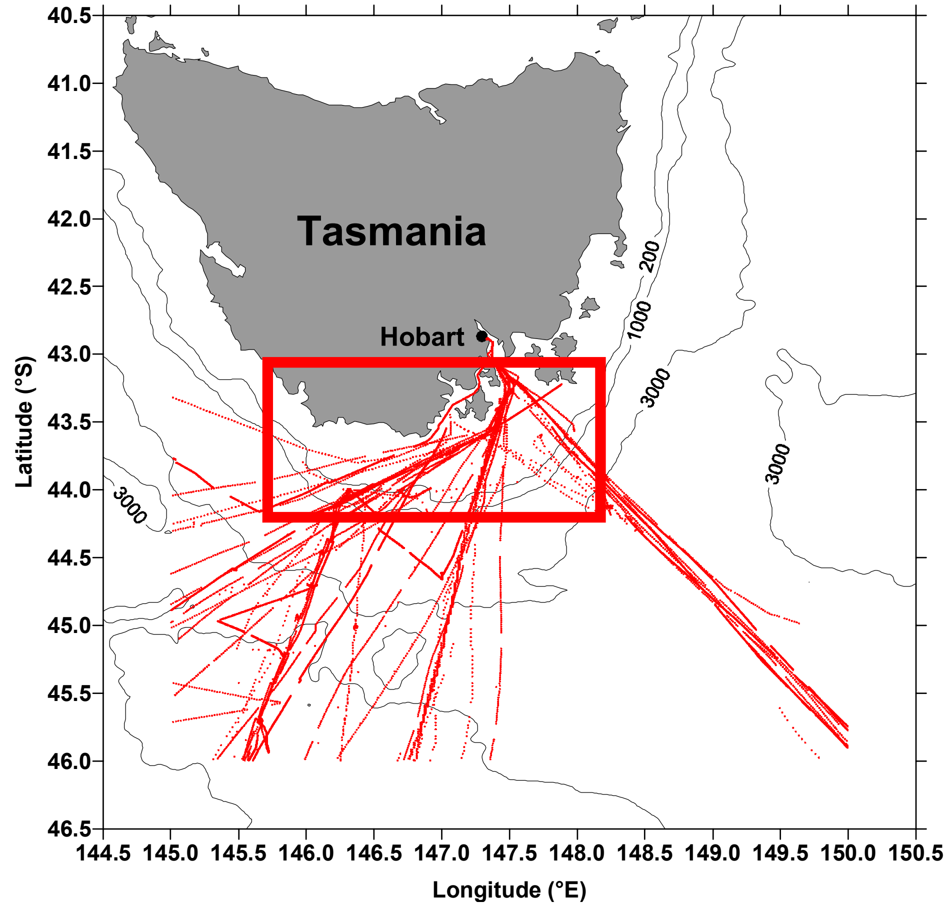
# Changes in stratification



# Changes in stratification : Tasman shelf



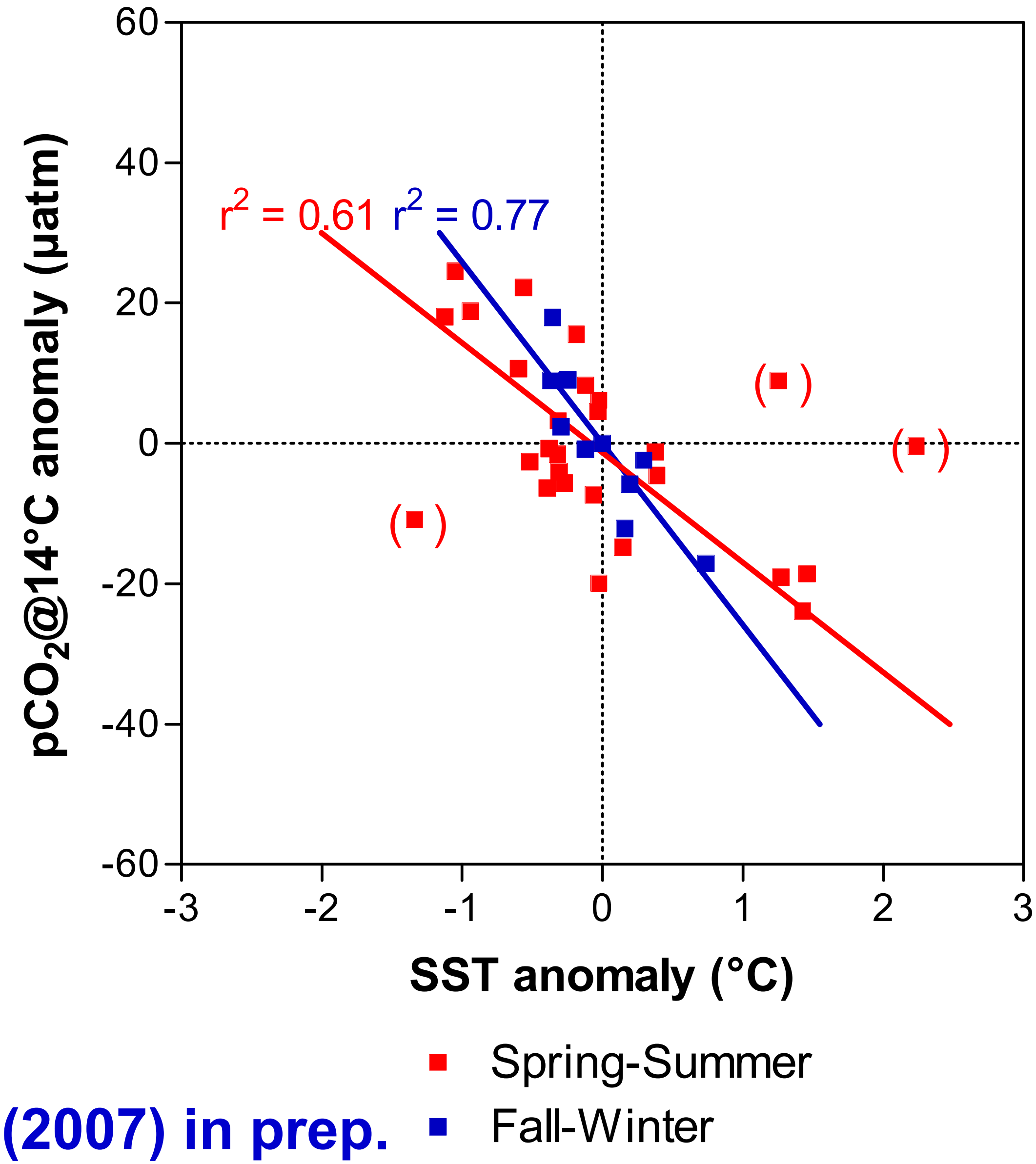

**40 transects obtained during 22 cruises from 1991 to 2003**




**Borges et al. (2007) in prep.**

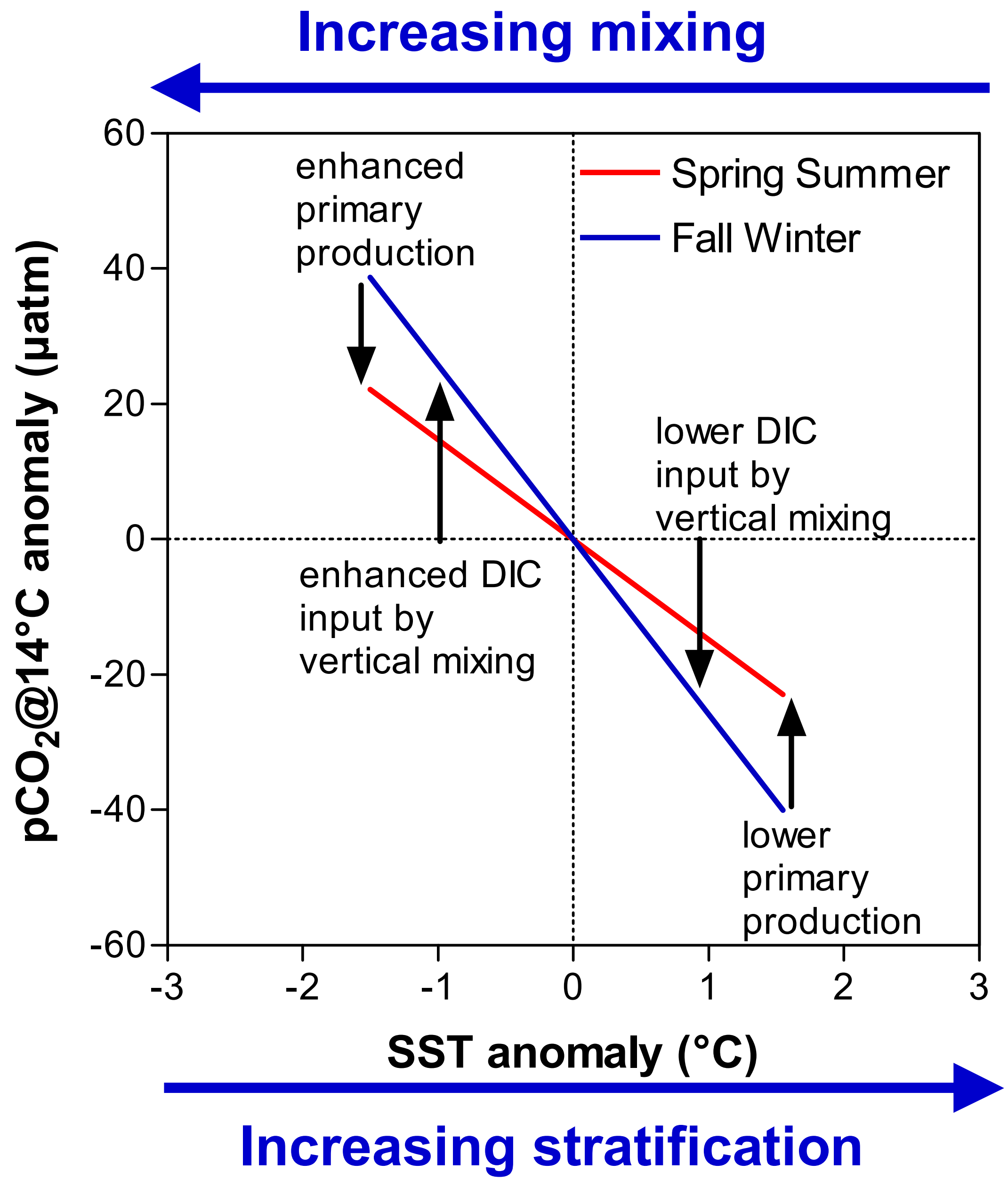
# Changes in stratification : Tasman shelf

## Monthly anomalies : $X' = X_{obs} - \langle X \rangle_{monthly}$



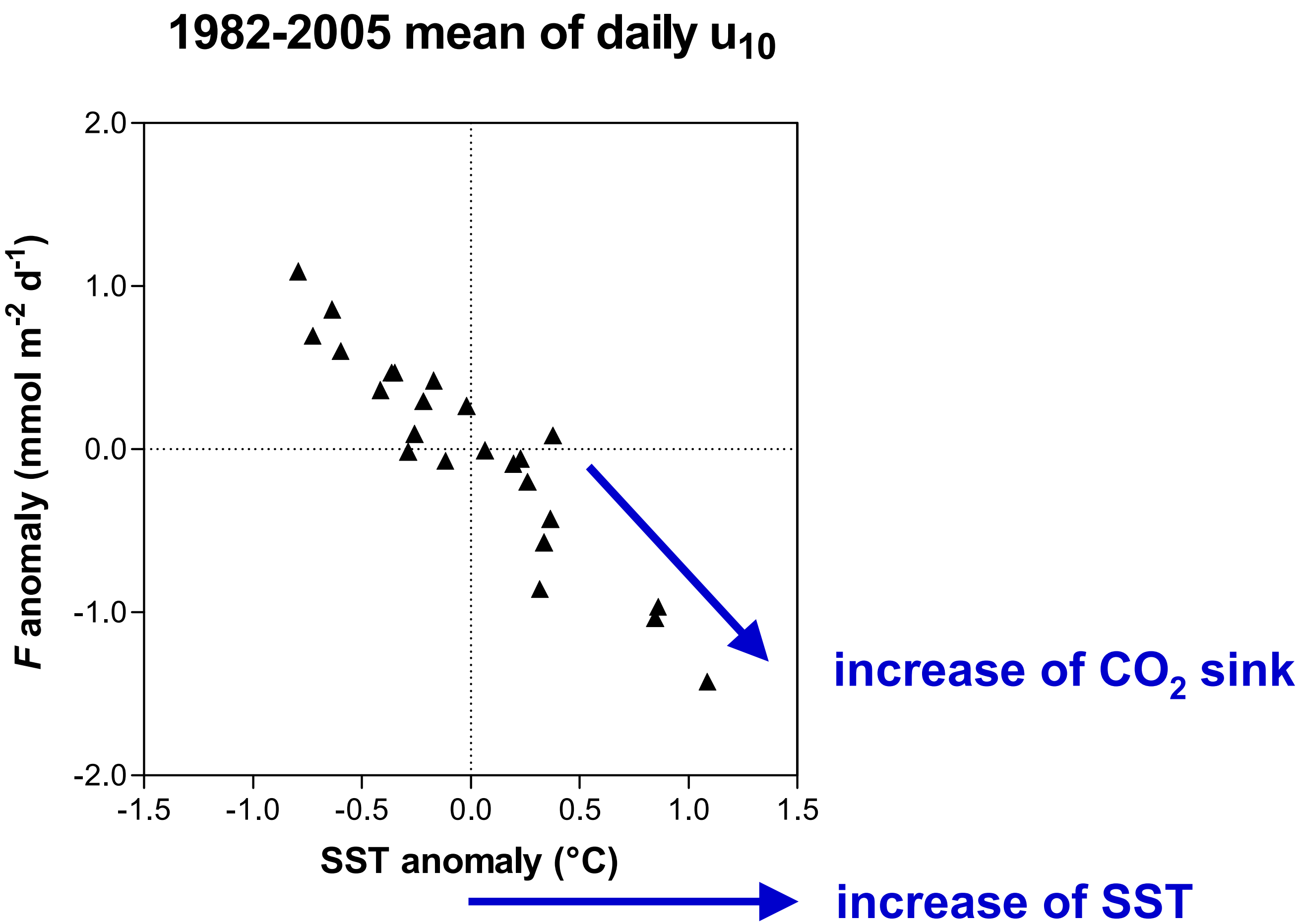

Borges et al. (2007) in prep.

# Changes in stratification : Tasman shelf




**Borges et al. (2007) in prep.**

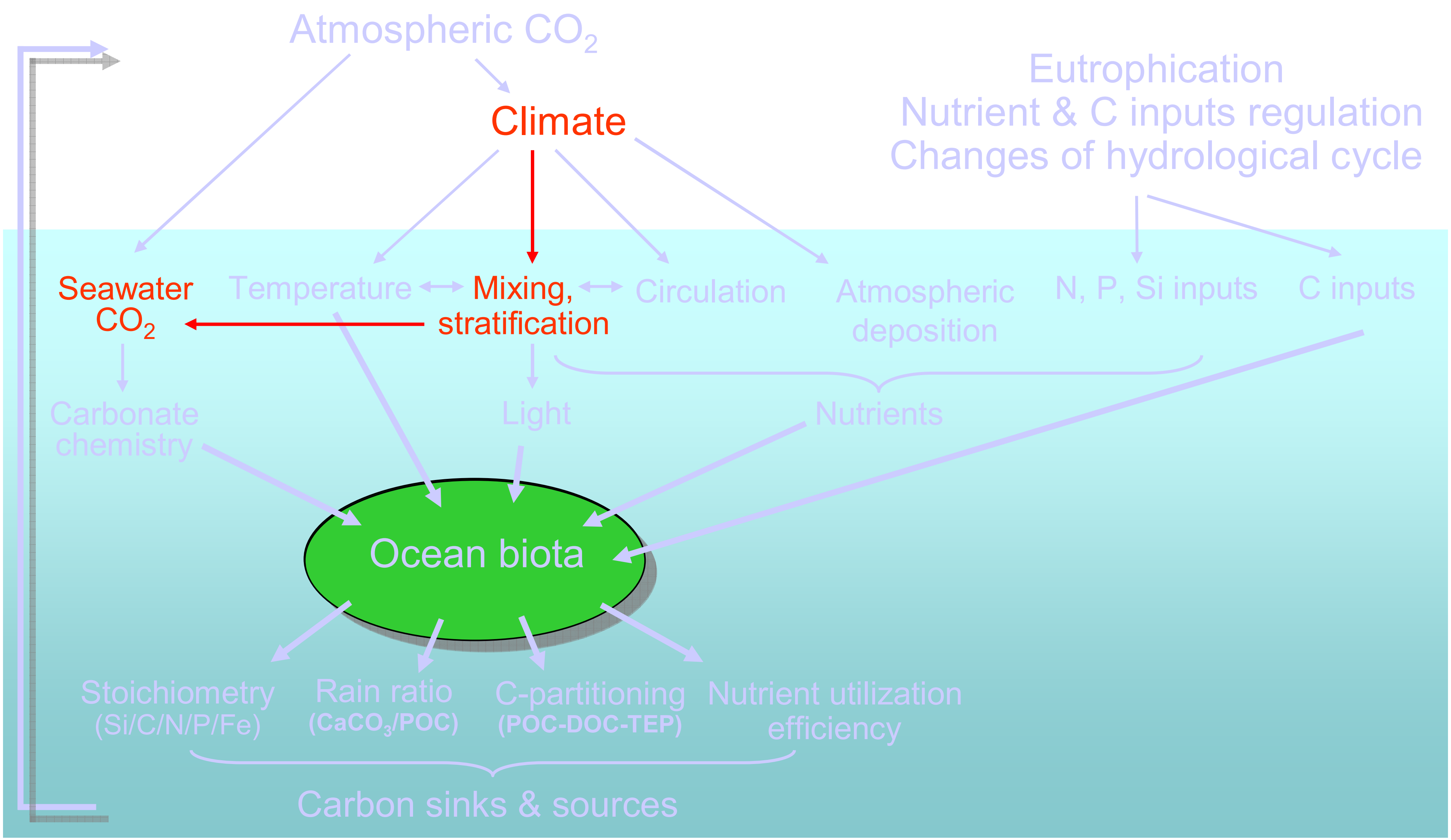
# Changes in stratification : Tasman shelf




↑ of 2°C in SST for 2100 at these latitudes from Hirst (1999) using IPCC "business-as-usual" IS92a radiative forcing scenario

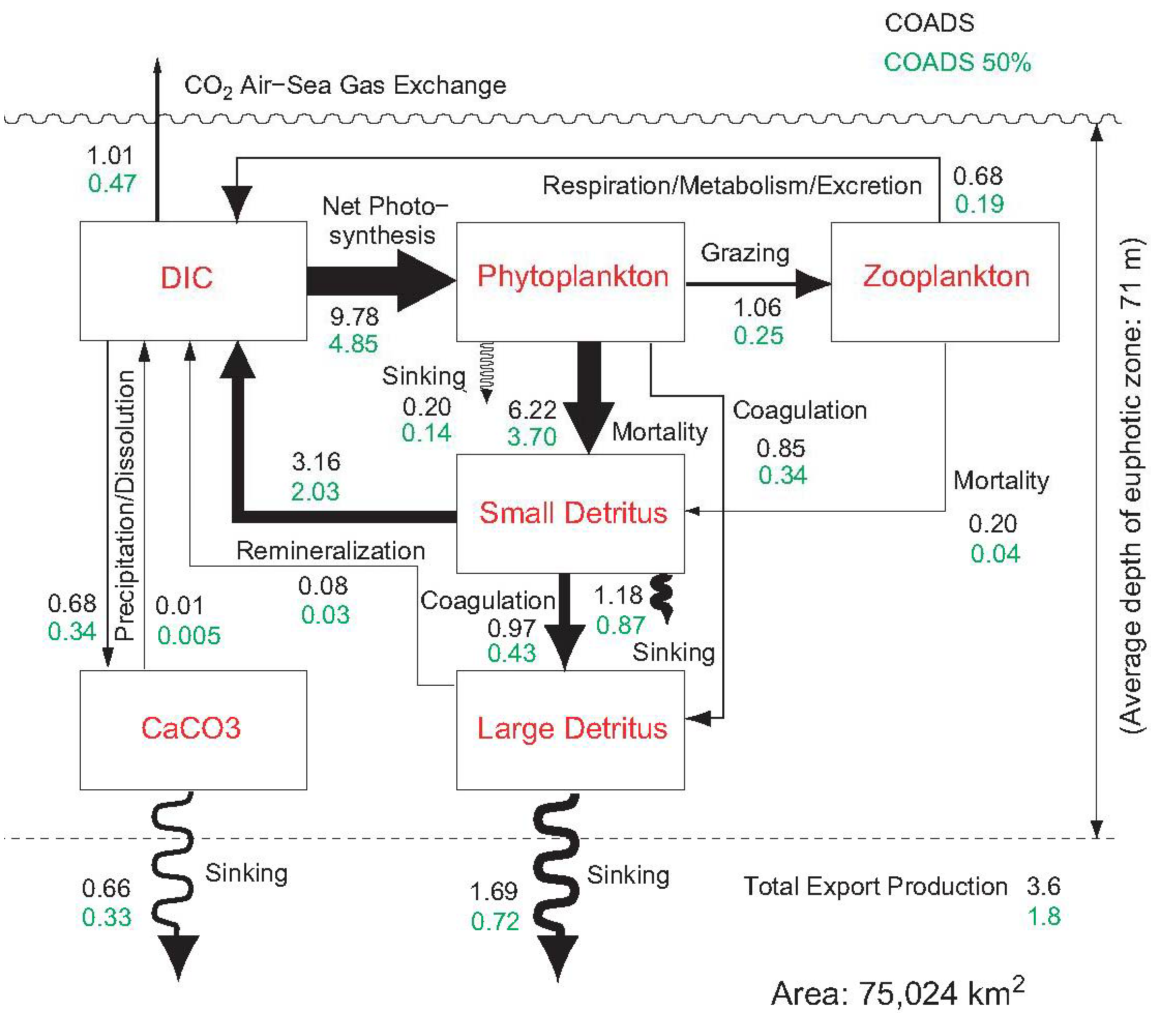
⇒ $CO_2$ sink -6.4 → -8.7 mmolC m$^{-2}$ d$^{-1}$ (~36% increase in $CO_2$ sink, strong negative feedback)

# Changes in coastal upwelling



# Changes in coastal upwelling

## California upwelling system




**50% reduction of wind stress**

**⇒ ↓ 50% in NPP**
**⇒ ↓ 75% in grazing**
**⇒ ↓ 50% in export pdt**
**⇒ ↓ 50% in $CO_2$ source**
**Mainly related to the ↓ vertical input of DIC and ↓ of *k***

**Plattner et al. (2005) SCOR conference "The ocean in a high $CO_2$ world"**

# Changes in coastal upwelling

PNAS

## Could $CO_2$-induced land-cover feedbacks alter near-shore upwelling regimes?

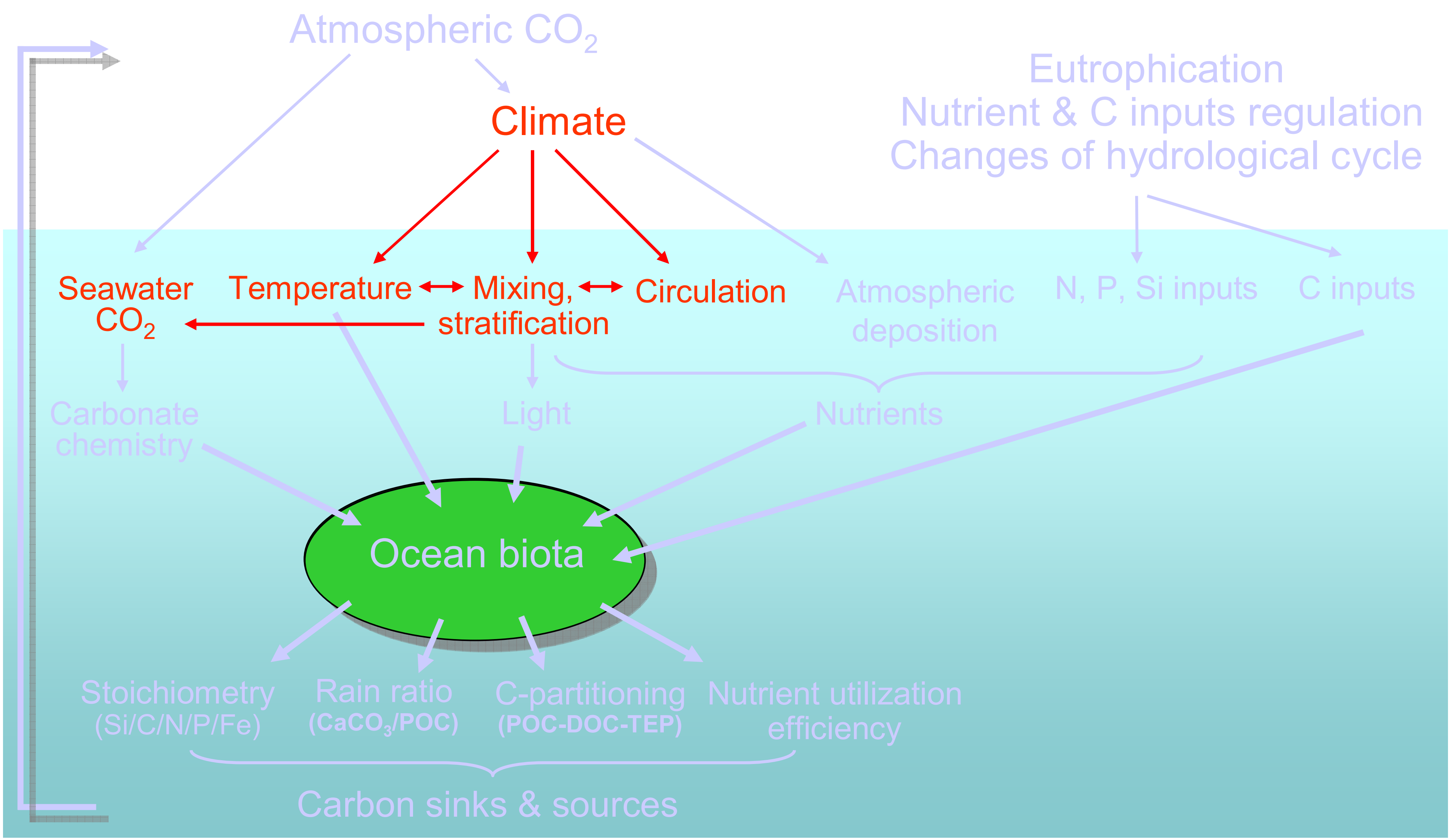
Noah S. Diffenbaugh*, Mark A. Snyder, and Lisa C. Sloan

Department of Earth Sciences, University of California, 1156 High Street, Santa Cruz, CA 95064

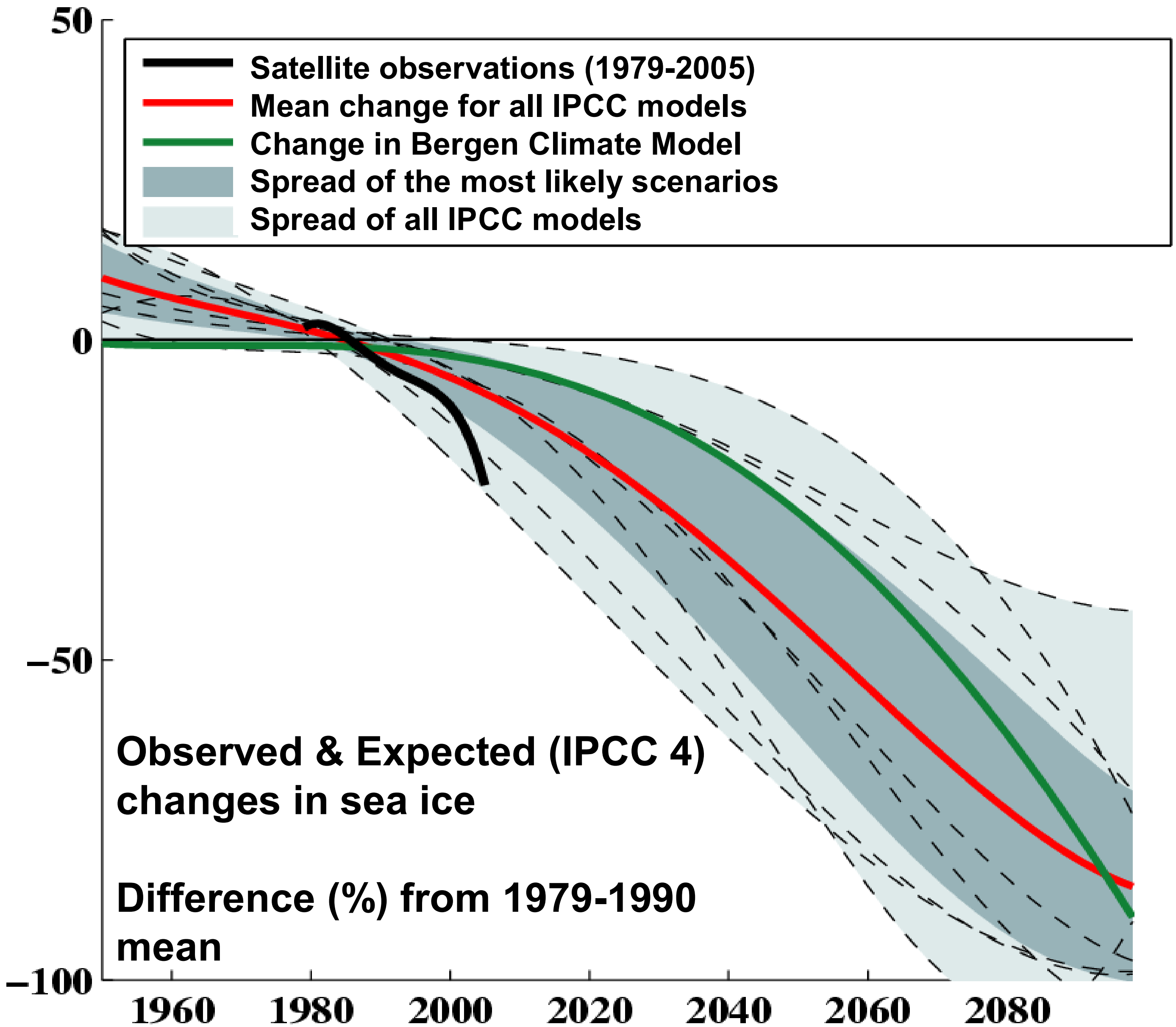
Edited by Susan Solomon, National Oceanic and Atmospheric Administration, Boulder, CO, and approved October 31, 2003 (received for review September 8, 2003)

**But climate change → increase in coastal upwelling**
**→ increase in $CO_2$ emission (?)**
**→ positive feedback on increasing atmospheric $CO_2$ (?)**

# Temperature change on the Arctic Ocean

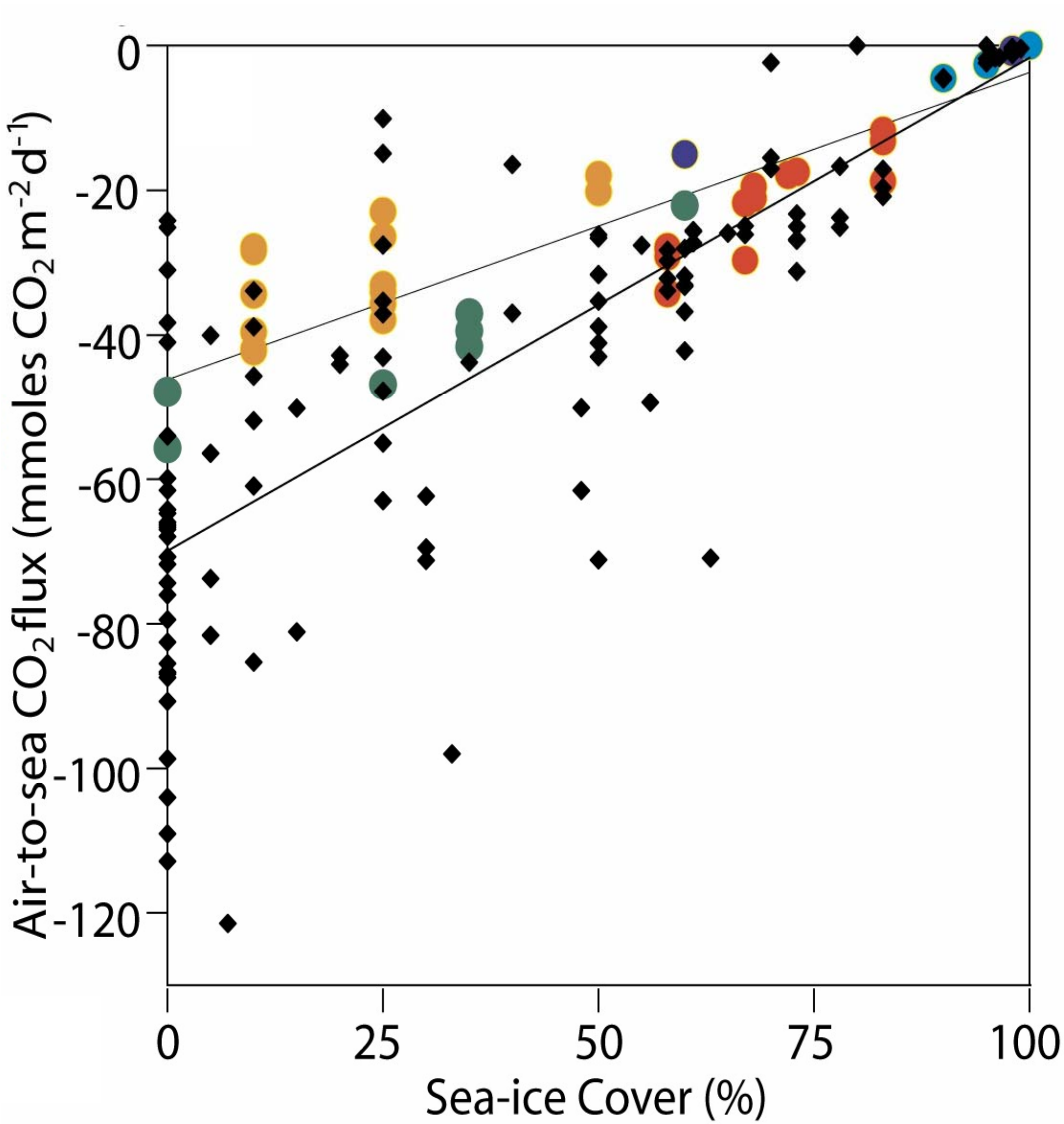


# Temperature change on the Arctic Ocean




**Olsen et al. (2007) SOVOC meeting**

# Temperature change on the Arctic Ocean



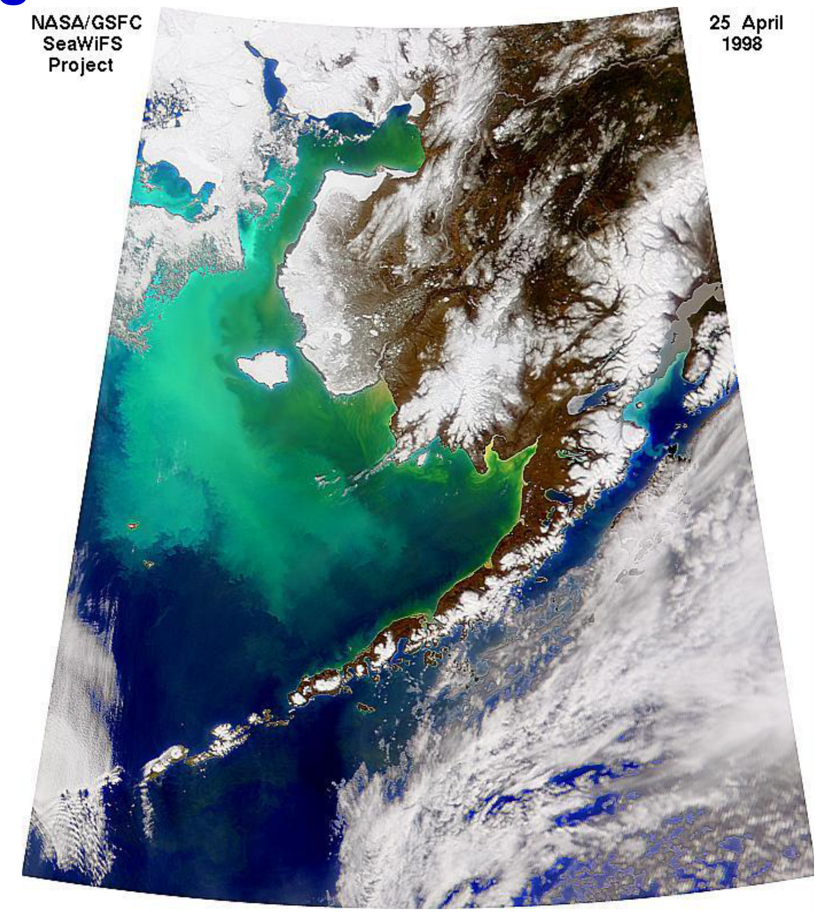

**Arctic Ocean sink for $CO_2$ has tripled over the last 3 decades (24 Tg yr$^{-1}$ to 66 Tg yr$^{-1}$) due to sea-ice retreat**

**Future sea-ice melting enhancing air-to-sea $CO_2$ flux by 28% per decade**

**Bates et al. (2006) GRL 33, L23609, doi:10.1029/2006GL027028**

# Temperature change on the Arctic Ocean

**Temperature change → Ecological regime shifts in the Arctic ?**
**e.g. occurrence of coccolithophorid blooms in the Bering Sea from 1997 onwards**



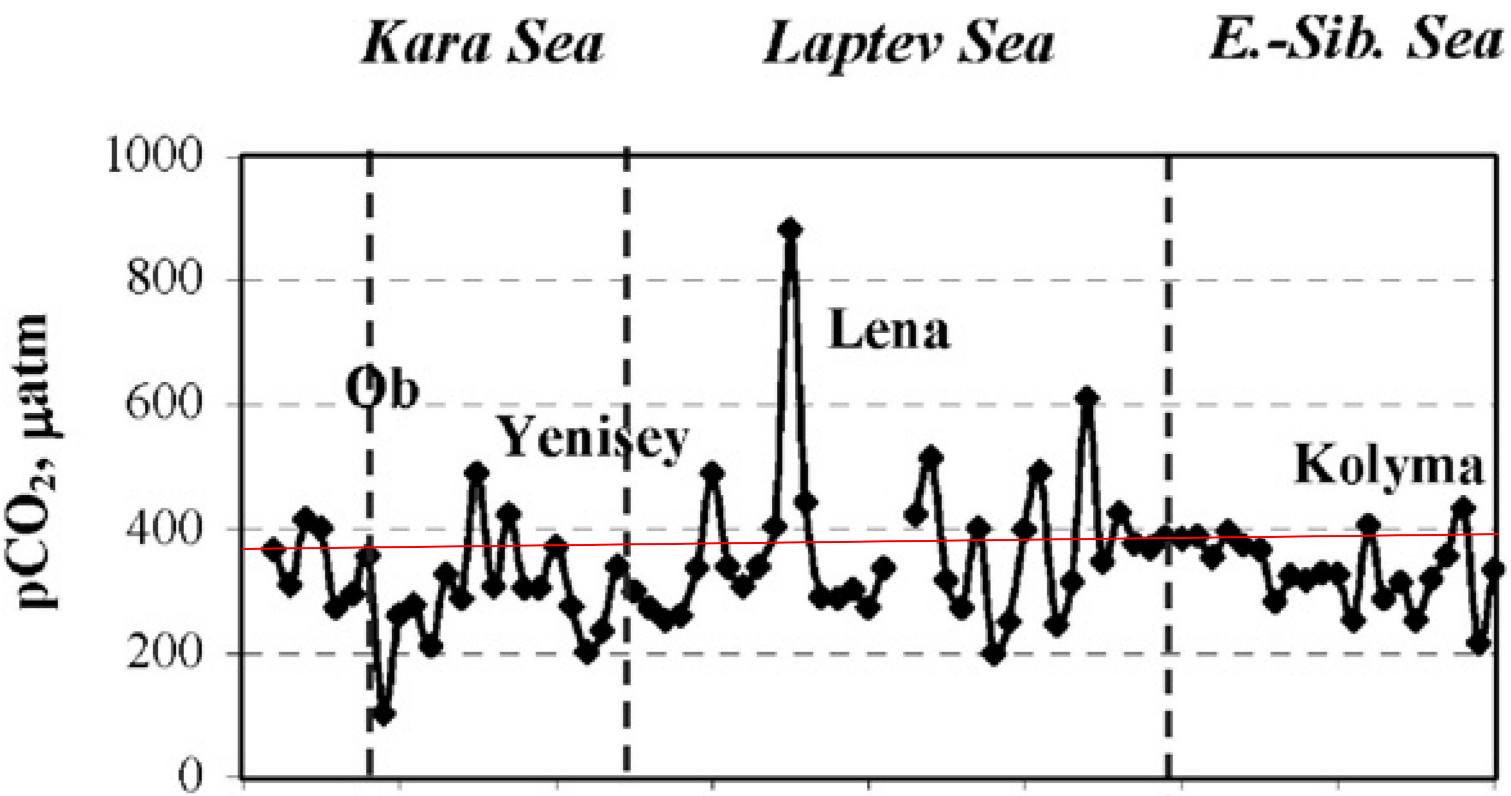

**Broerse et al. (2003) Cont. Shelf Res., 23:1579–1596.**
**Merico et al. (2003) GRL, 30, 1337, doi:10.1029/2002GL016648.**

# Temperature change on the Arctic Ocean

**9400 PgC organic C buried in the 100 m of tundra and taiga**

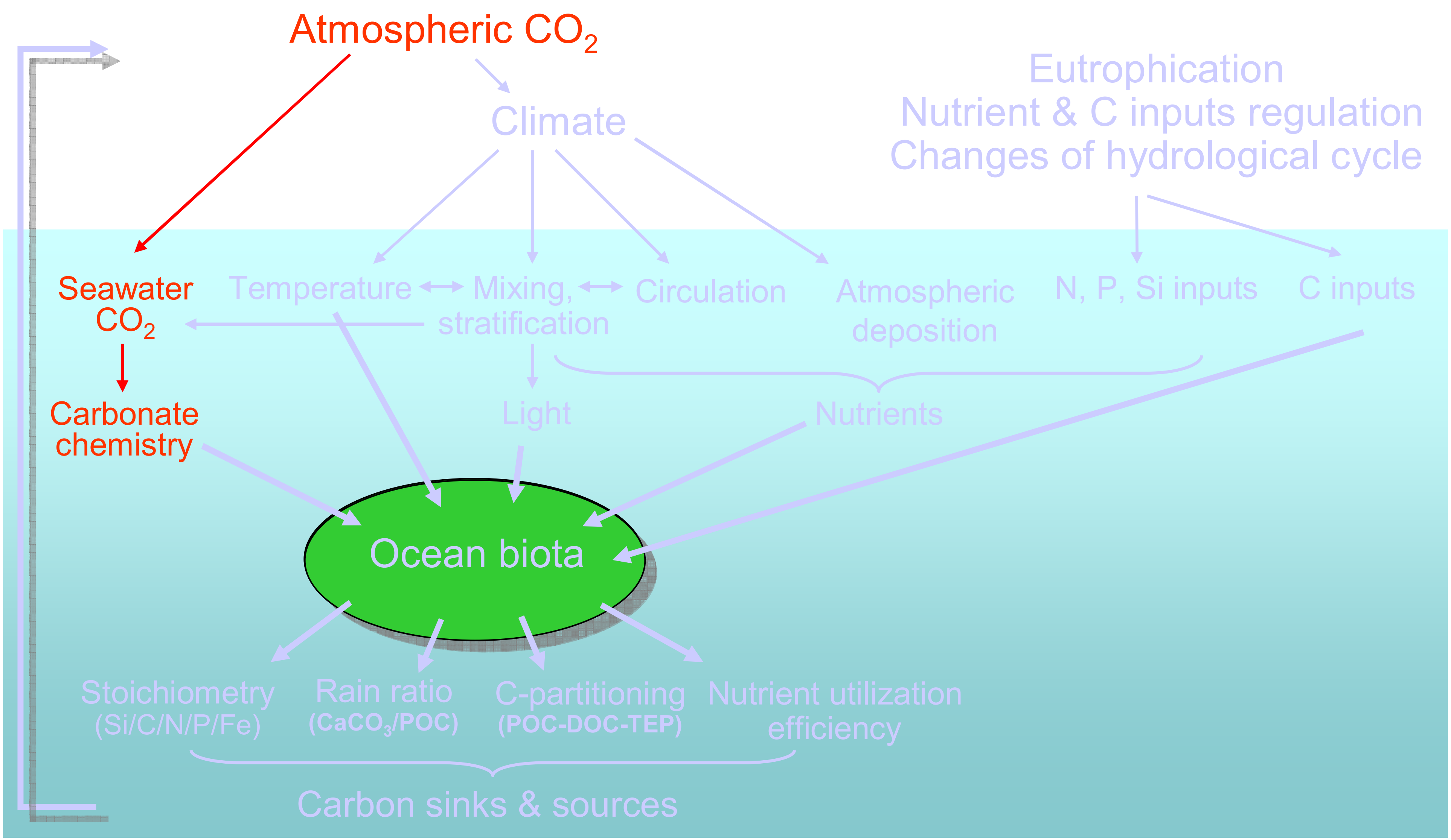
**Permafrost thawing**
**Coastal Erosion**
**Increased precipitation**

$\Big\}$ **can mobilise organic carbon**
**increase $CO_2$ source of near-shore zones**

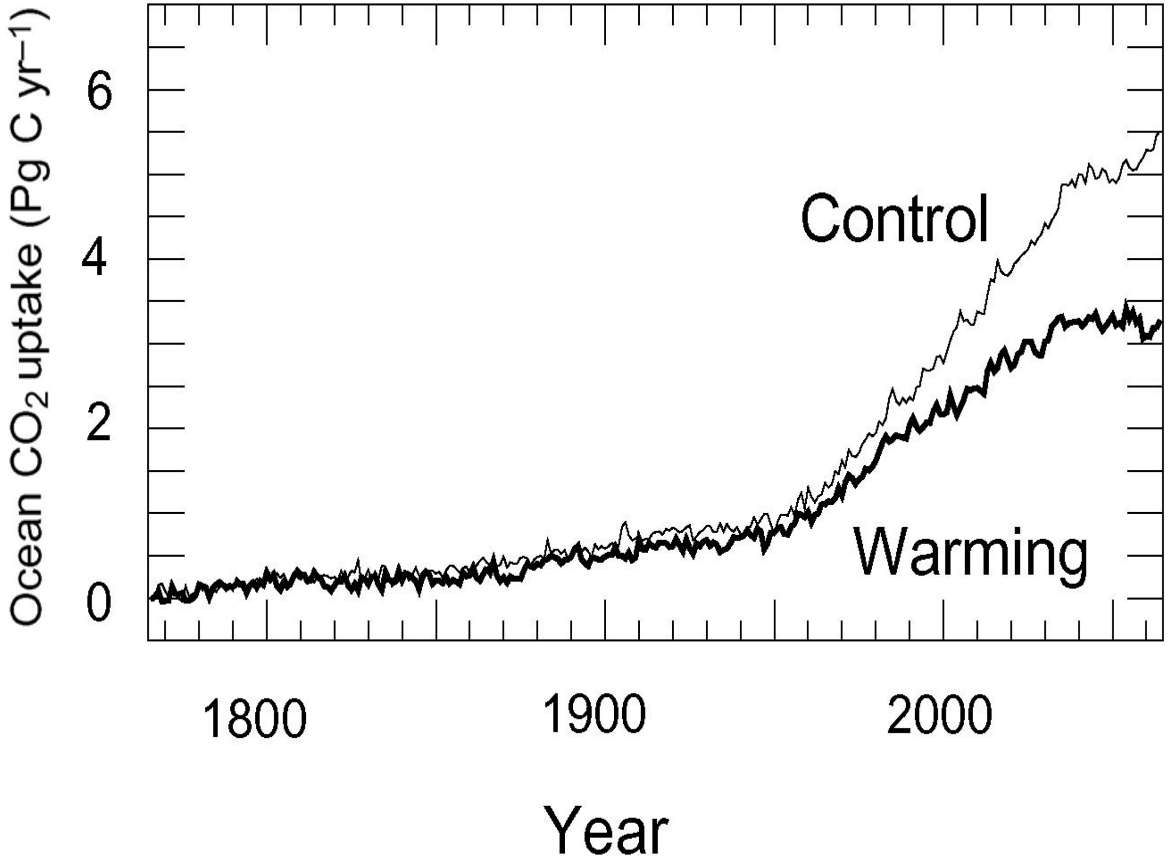



**Semiletov et al. (2007) JMS 66: 204–226**

# Ocean acidification : buffer factor



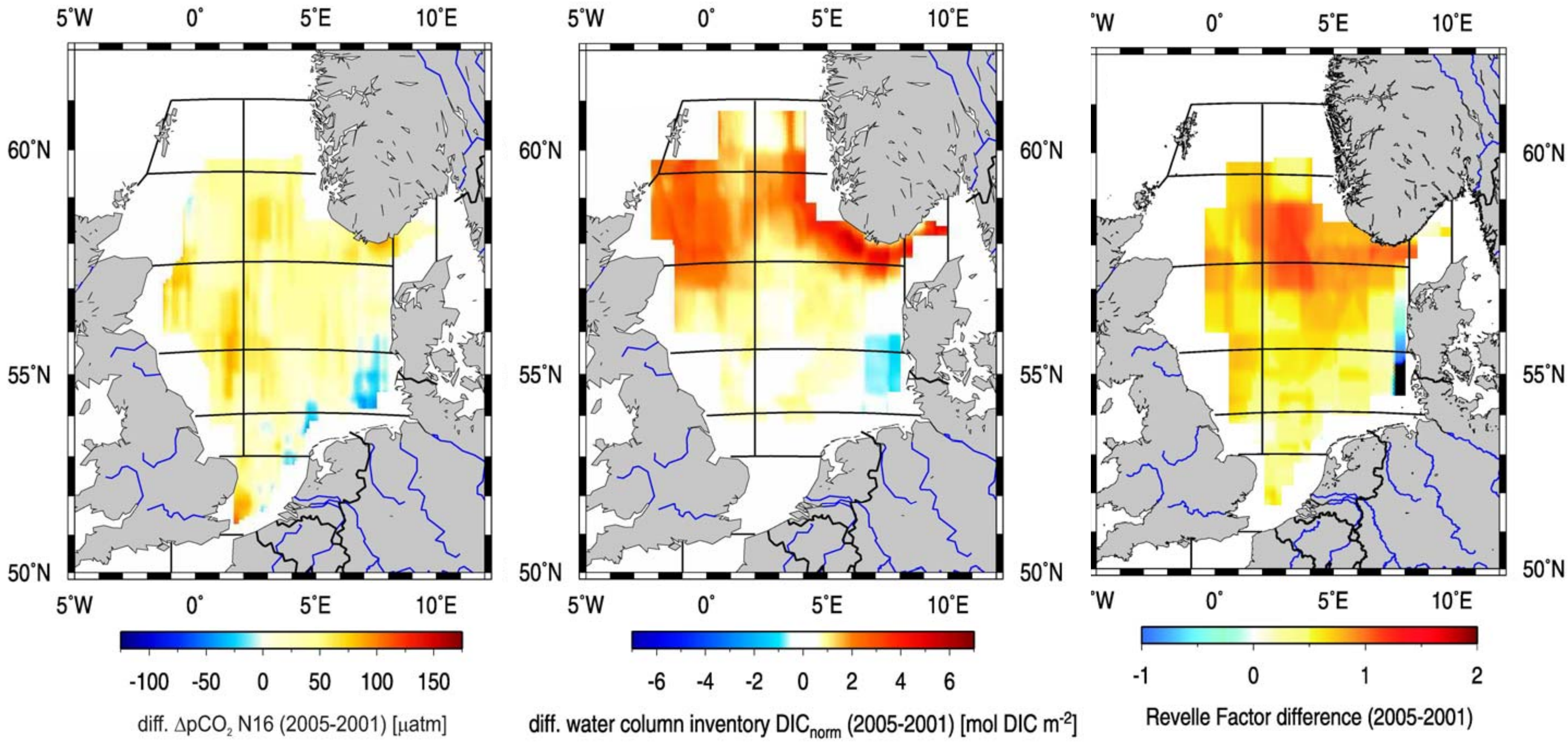
# Ocean acidification : buffer factor




**Penetration of $CO_2$ into the oceans**
**⇒ decrease of the buffer capacity of seawater**
**⇒ reduces the uptake of anthropogenic $CO_2$**

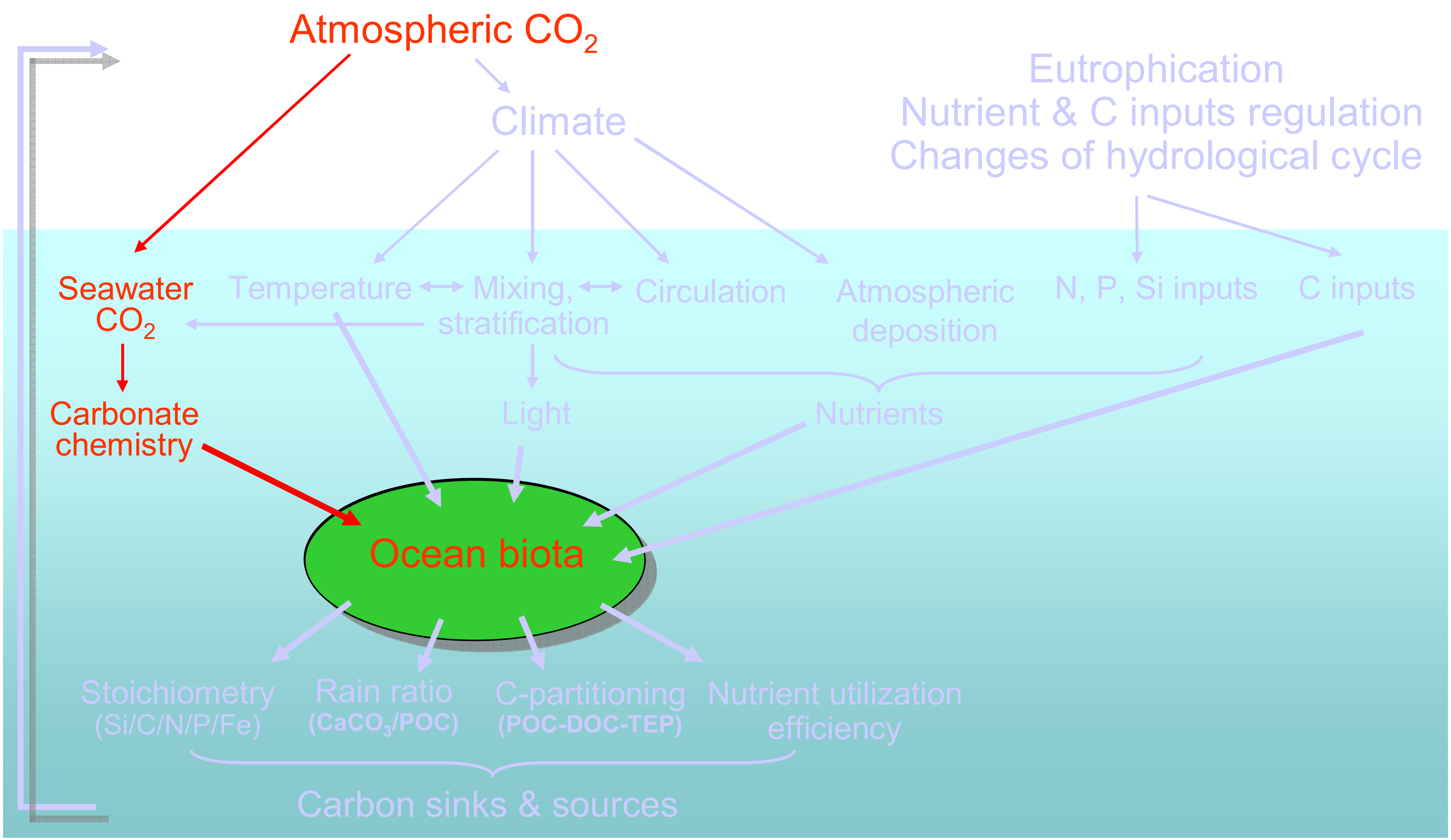
**Sarmiento et al. (1998) Nature 393:245-249**

# Ocean acidification : buffer factor




**Thomas et al. (2007) GBC, doi:10.1029/2006GB002825**
**Thomas et al., Tuesday 18$^{th}$ 14:00**

# Ocean acidification : effects on biota



# Ocean acidification : calcification

## Calcification :

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2O + CO_2$$
$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

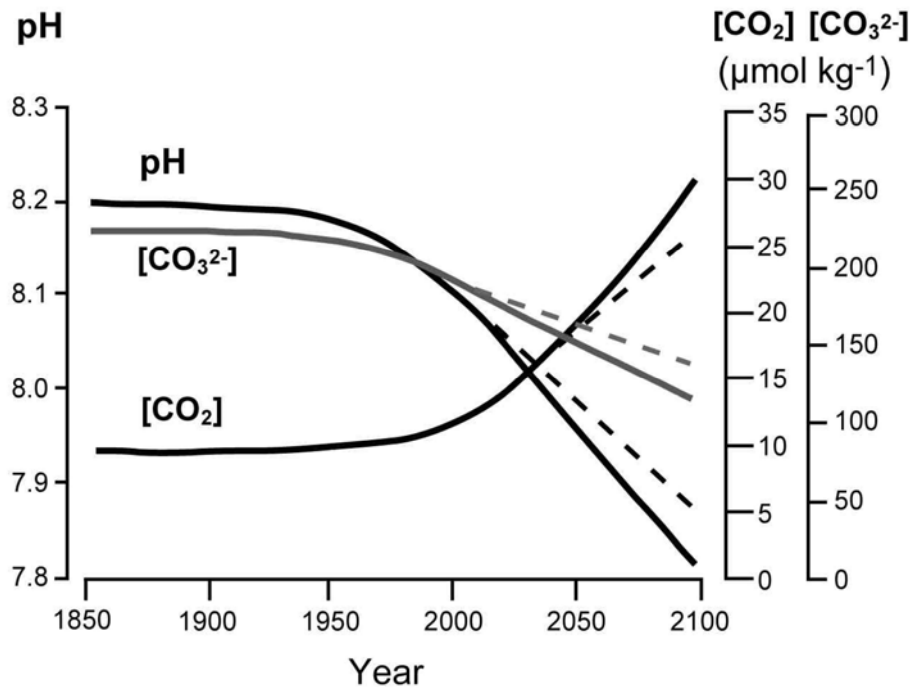



**Fig. 2.** Seawater pH and the dissolved carbon dioxide ($CO_2$) and carbonate ion ($CO_3^{2-}$) concentrations in the surface layer of the ocean assuming a "business as usual" (IS92a) anthropogenic $CO_2$ emission scenario (Houghton et al. 1995). Dashed lines represent the predicted changes in carbonate chemistry if $CO_2$ emissions are reduced according to the Kyoto Protocol (modified after Wolf-Gladrow et al. 1999).

**Increase in $CO_2$**
**→ decrease of calcification**
**→ negative feedback**

Rost & Riebesell (2004) in *Coccolithophores. From Molecular Processes to Global Impact*

# Ocean acidification : calcification

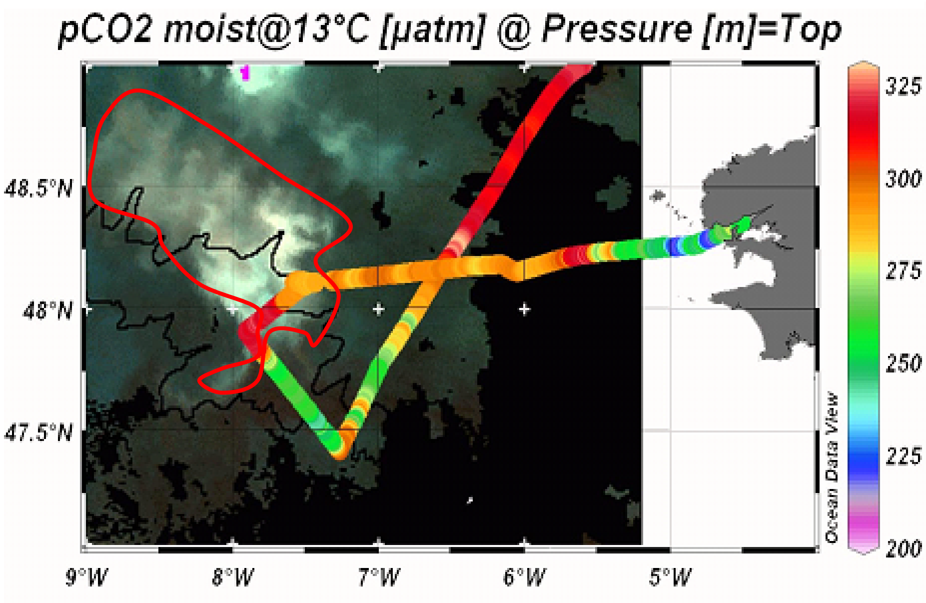
## Based on Suzuki & Kawahata (2003) and Bates (2002)

| | $pCO_2$ coral reef – $pCO_2$ocean (ppm) |
|---|---|
| Christmas Island | -80 |
| Shiraho reef | 7 |
| Fanning atoll | 30 |
| Canton atoll | 15 |
| Palau reef | 46 |
| Majuro atoll | 23 |
| South Male atoll | 6 |
| Northern Great Barrier Reef | 29 |
| Southern Great Barrier Reef | 12 |
| Hog reef (1994) | 26 |
| Hog reef (1995) | 16 |
| Hog reef (1996) | 16 |
| | |
| Average | 12 |

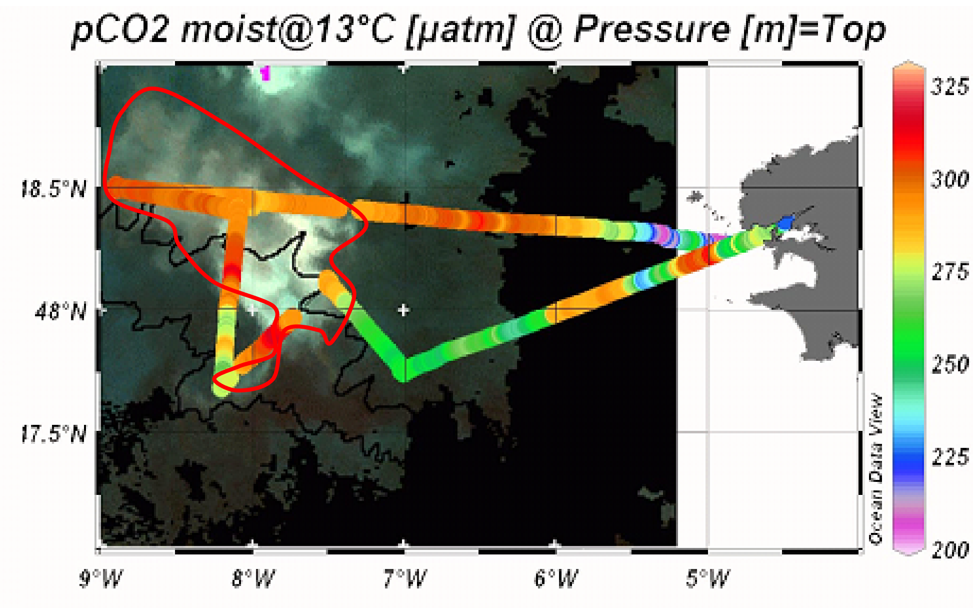
# Ocean acidification : calcification

## Coccolithophorid bloom in the Gulf of Biscay (June 2006)

LEG 1



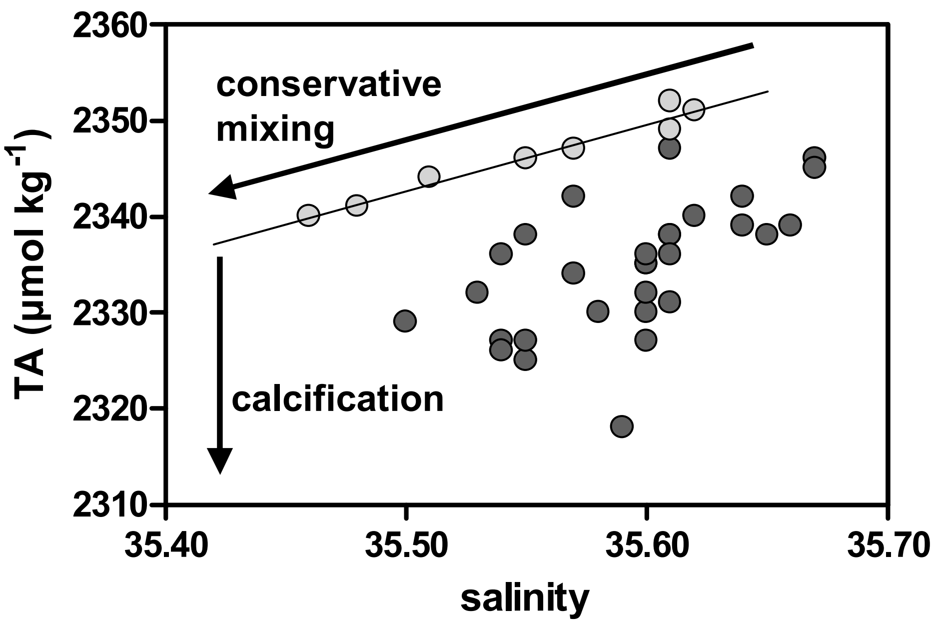

LEG 2

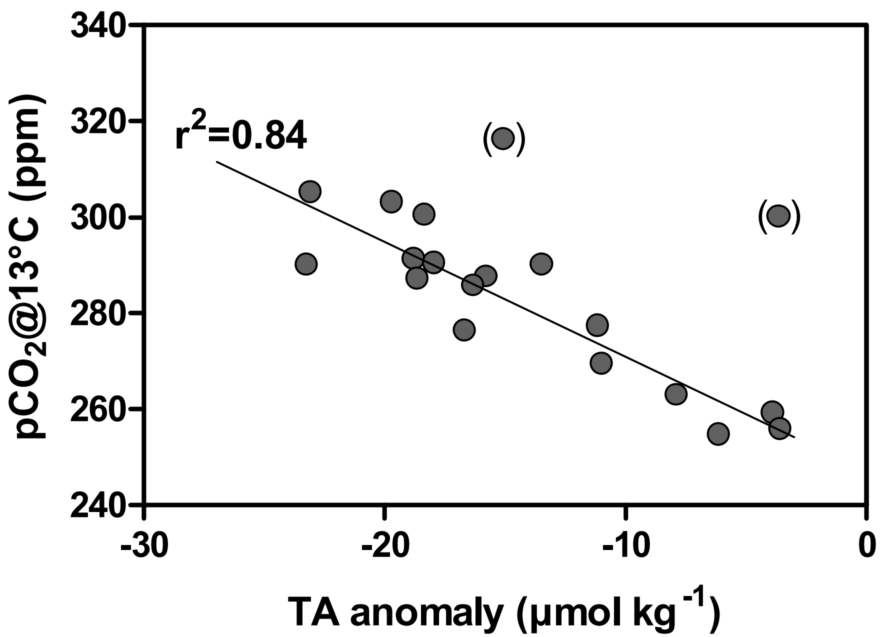



Suykens & Borges (unpubl.) PEACE project

# Ocean acidification : calcification

## Coccolithophorid bloom in the Gulf of Biscay (June 2006)

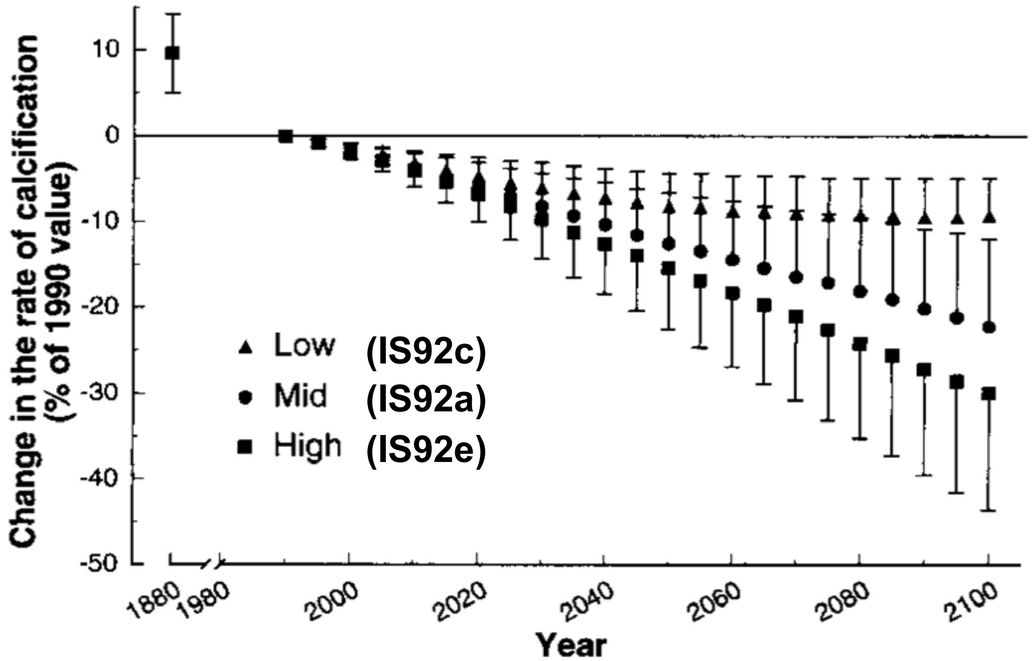



**Suykens & Borges (unpubl.) PEACE project**

# Ocean acidification : calcification

## Coral reef calcification feedback on increasing atmospheric $CO_2$




↓ 22 % of coral reef calcification for 2100 ("business-as-usual" IS92a IPCC) (Gattuso et al. 1999)

Present day coral reef calcification 0.072 PgC $yr^{-1}$ (Gattuso et al. 1998)

⇒ feedback of 0.009 PgC $yr^{-1}$ (with $\Psi = 0.6$ from Frankignoulle et al. 1994)

Small compared to the overall sink of -0.45 PgC $yr^{-1}$ of marginal seas

# Ocean acidification : calcification

## Pelagic calcification feedback on increasing atmospheric $CO_2$

**Global pelagic calcification 0.6 – 1.6 PgC $yr^{-1}$ (Balch et al. 2007)**

**Coastal pelagic calcification 0.1 – 0.3 PgC $yr^{-1}$ (based on Balch et al. 2005)**

**Doubling of atmospheric $CO_2$ for 2100 ("business-as-usual" IS92a IPCC scenario)**

**⇒ decrease of coastal pelagic calcification of 0.006 – 0.016 PgC $yr^{-1}$ (based on Gehlen et al. 2007)**

**⇒ feedback of 0.004 – 0.010 PgC $yr^{-1}$ (with $\Psi$ = 0.6 from Frankignoulle et al. 1994)**

**Small compared to the overall sink of -0.45 PgC $yr^{-1}$ of marginal seas**

# Ocean acidification : effects on biota

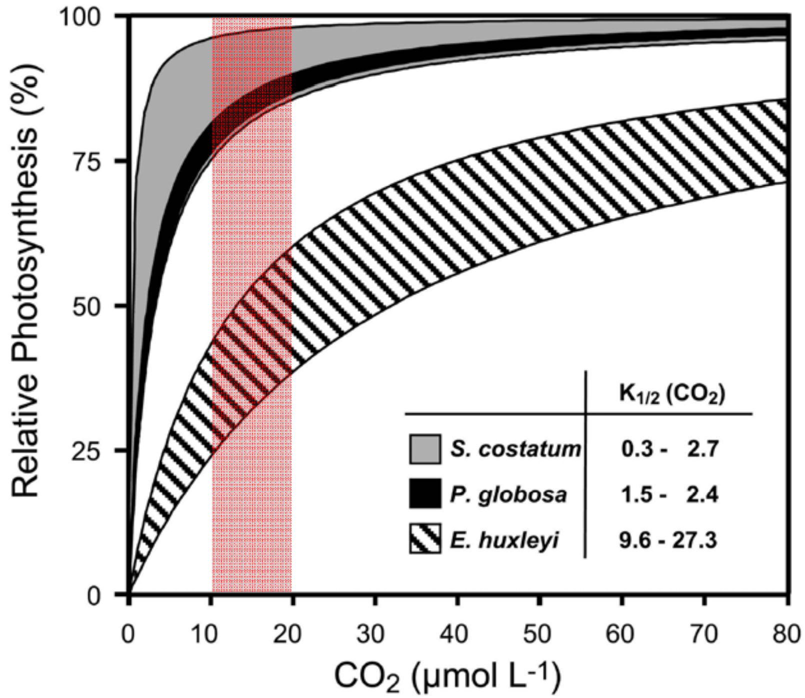



**Fig. 5.** Photosynthesis of phytoplankton species differs with respect to $CO_2$ sensitivity: While most species (here *Skeletonema costatum* and *Phaeocystis globosa*) are at or close to $CO_2$ saturation at present day $CO_2$ levels (8–20 µmol $L^{-1}$), coccolithophores such as *E. huxleyi* have comparatively low affinities for inorganic carbon and appear to be carbon-limited in today's ocean. This raises the possibility that coccolithophores may benefit directly from the present increase in atmospheric $CO_2$. The range in half-saturation concentrations ($K_{1/2}$; in µmol $L^{-1}$) for photosynthesis shown here reflects the degree of regulation as a function of $pCO_2$ during growth (according to Rost et al. 2003). Highest apparent affinities for $CO_2$ were generally observed in cells which were grown under low $pCO_2$.

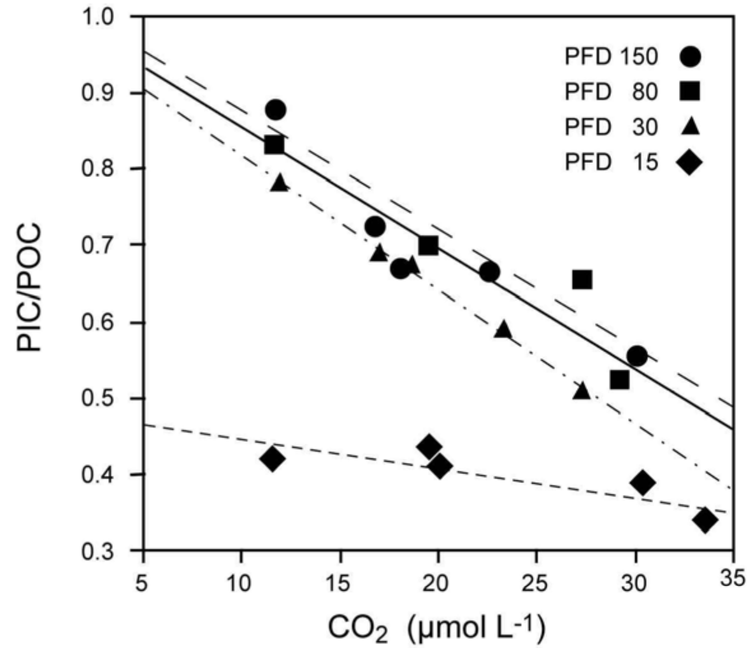
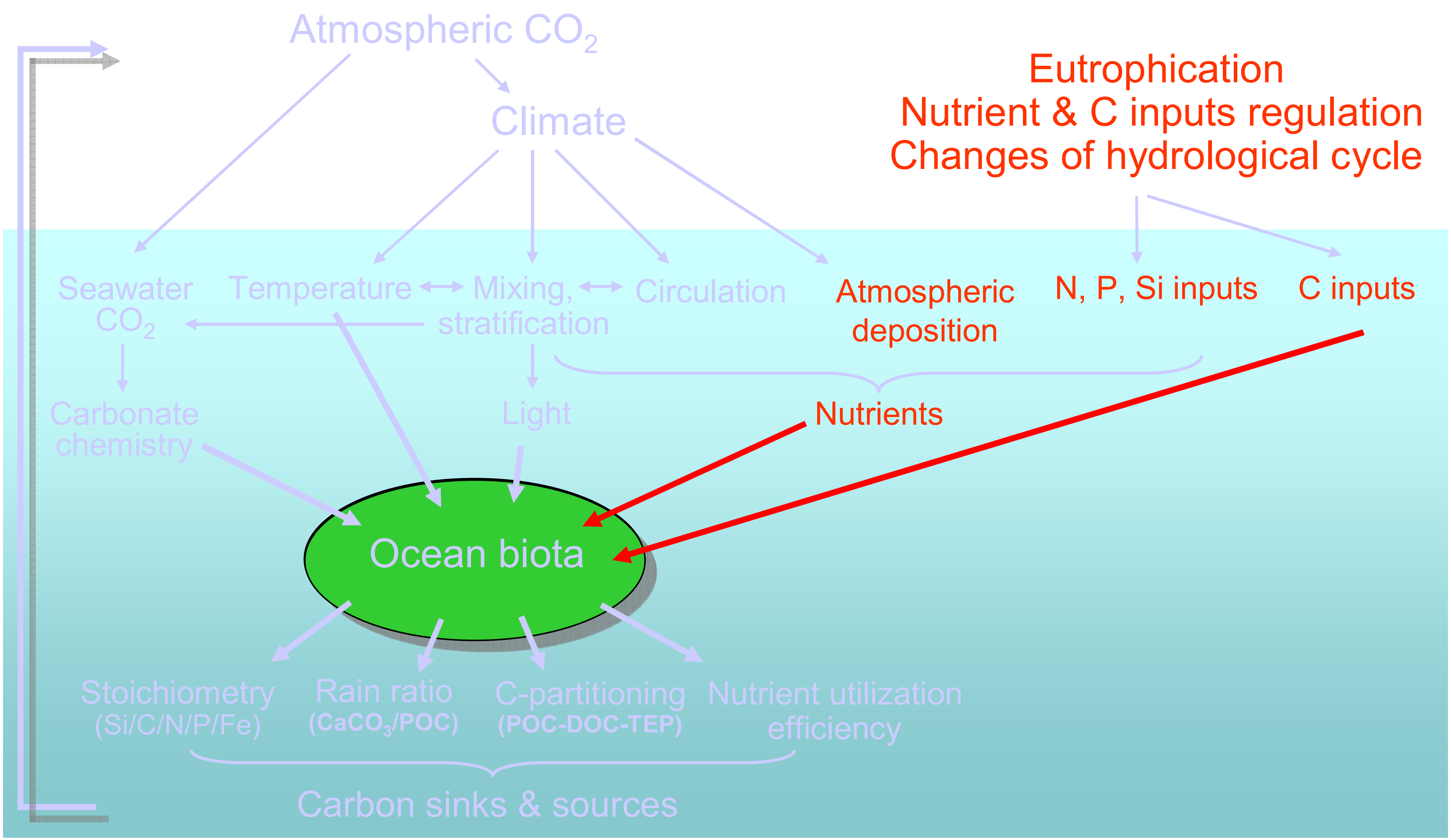



**Fig. 6.** Rising $CO_2$ decreases the ratio of calcification to organic carbon production (PIC/POC) in *E. huxleyi*. The decrease in PIC/POC is caused by enhanced photosynthetic carbon fixation and reduced or constant calcification. This trend is consistent over a range of photon flux densities (PFDs; in µmol photons $m^{-2}$ $s^{-1}$), yet declines under severe light-limitation (modified after Zondervan et al. 2002).

**Rost & Riebesell (2004) in *Coccolithophores. From Molecular Processes to Global Impact***

# Nutrient and C inputs



# Nutrient and C inputs

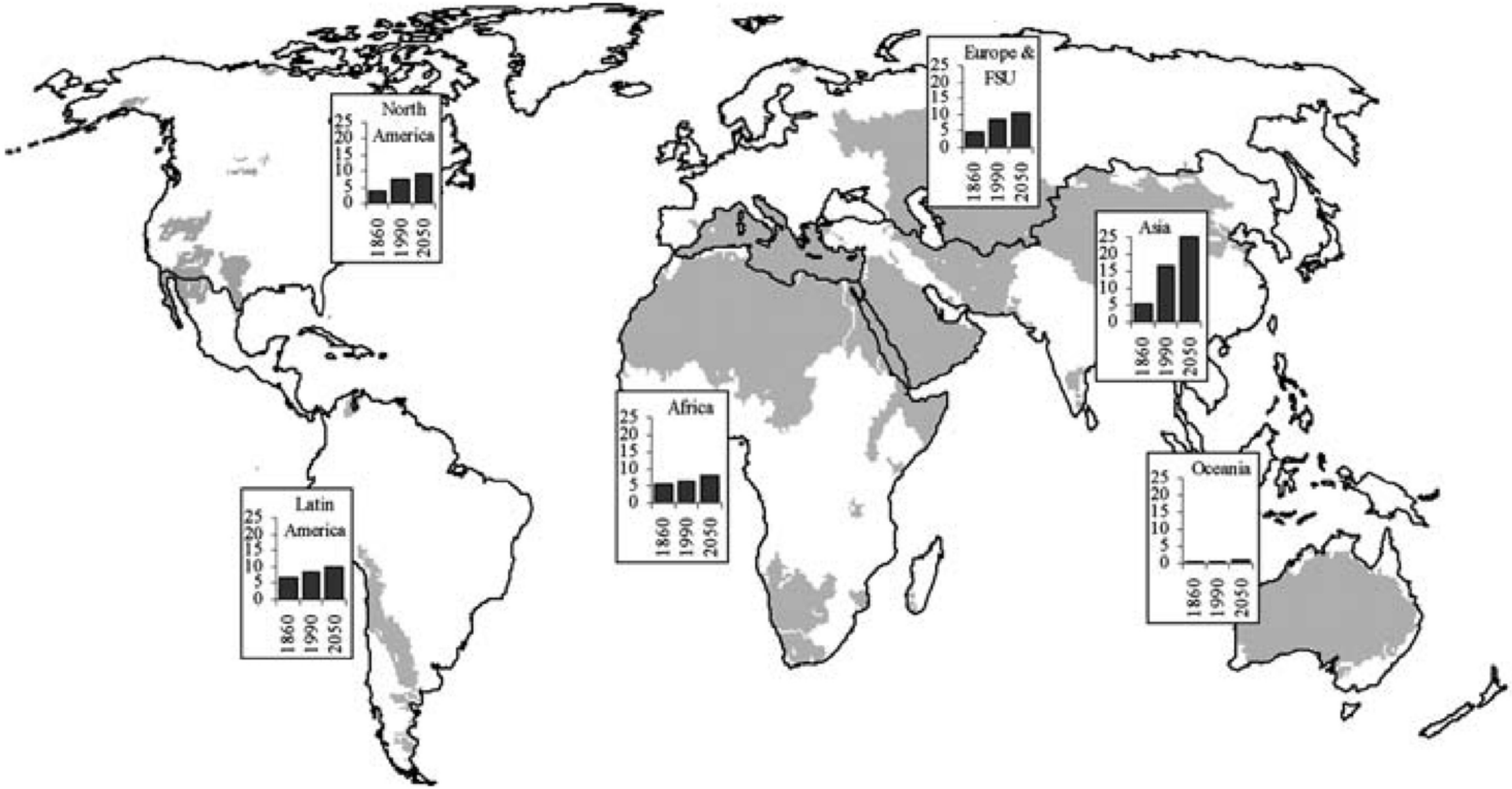



*Figure 5.* Riverine Nr export to the coastal zone (Tg N $yr^{-1}$) in the past (1860 Left bar), present (1990 Center bar) and future (2050 Right bar). Dry and inland watershed regions that do not transmit to coastal areas are shown in gray.

**Galloway et al. (2004) Biogeochemistry 70:153-266**

# Nutrient and C inputs

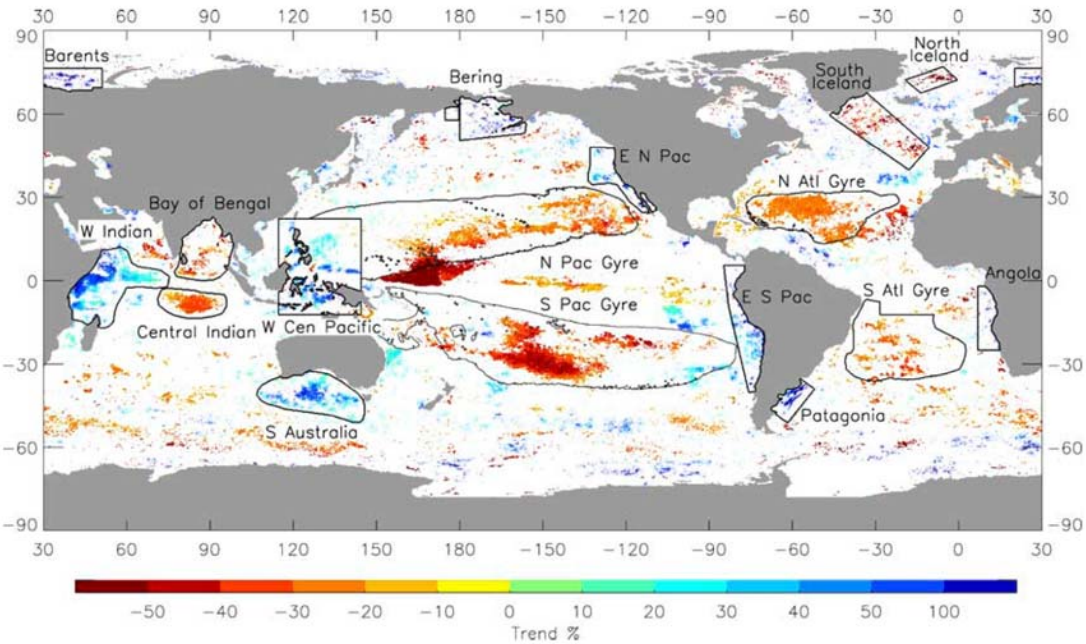



**Figure 1.** Regions defined by coherent distribution of 25-km grid points where chlorophyll concentrations indicated a significant trend ($P < 0.05$) over the 6-year data record of SeaWiFS. Only regions where significance was found within the region as a whole are shown here.

**Table 1.** Global Trends in Ocean Chlorophyll 1998–2003[a]

| Region | N | Slope | Intercept | Error | Trend | Significance |
|---|---|---|---|---|---|---|
| Global | 560247 | 0.00261 | −0.007 | ±0.002 | +4.13% | P < 0.05 |
| Coastal | 51979 | 0.03687 | −0.092 | ±0.033 | +10.35% | P < 0.05 |
| Open Ocean | 530579 | 0.00040 | −0.001 | ±0.003 | +0.90% | NS |

[a]NS indicates not statistically significant at the 95% confidence level. N is the maximum number of values in a given year, error represents the standard error of the estimate, and trend is reported as percent change over 6 years.

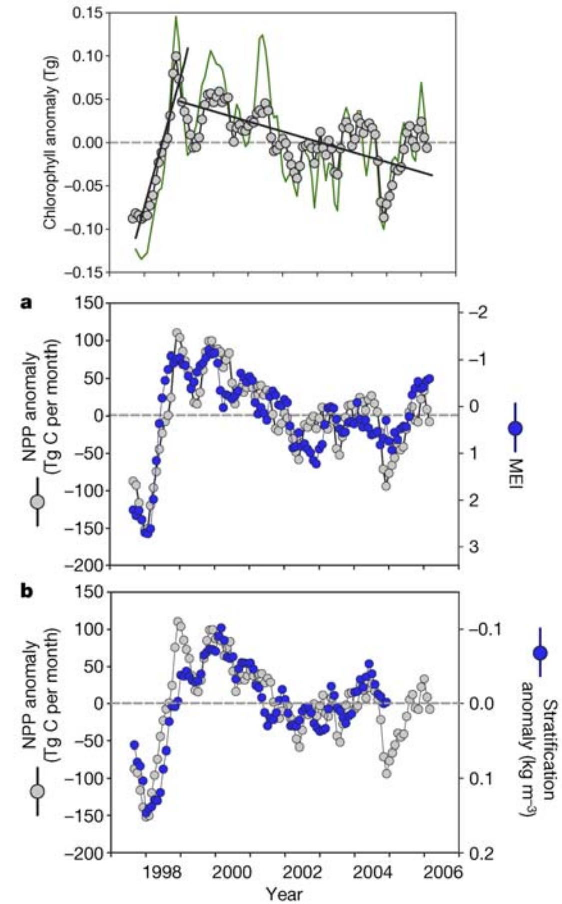


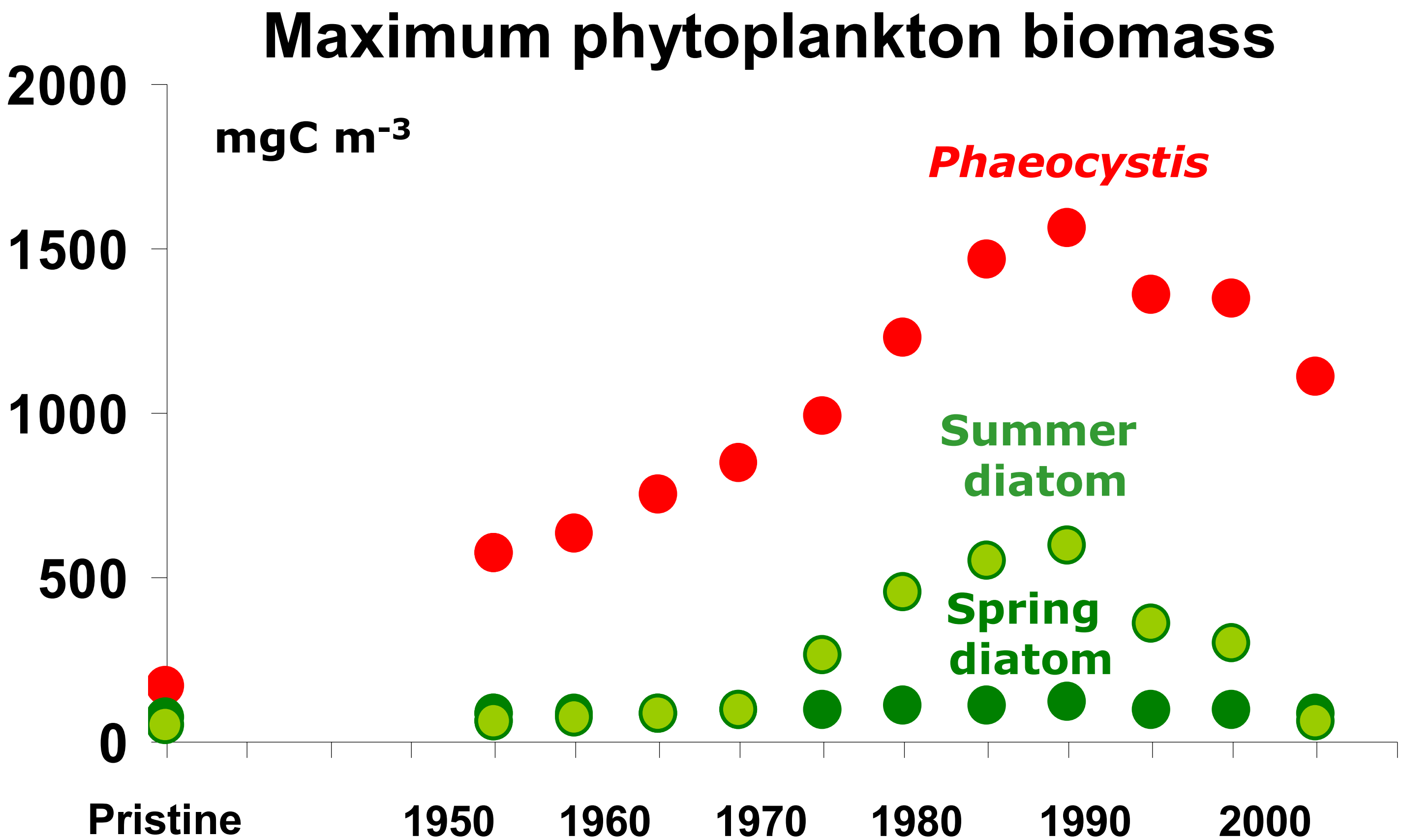

**Figure 2 | Ocean productivity is closely coupled to climate variability.** **a**, NPP anomalies in the permanently stratified oceans (grey symbols, left axis) are highly correlated ($r^2 = 0.77$) with the MEI of climate variability (red symbols, right axis). NPP data are from Fig. 1c. **b**, Changes in ocean stratification (red symbols, right axis) link climate variability to ocean biology, and are well correlated ($r^2 = 0.73$) with NPP anomalies (grey symbols, left axis) in ocean regions with annual average surface temperatures over 15 °C. Stratification strength was assessed as the density differences between the surface and a depth of 200 m using SODA data (see Methods). Publicly accessible SODA data are available only to the end of 2004. Note that the MEI and stratification axes (right) increase from top to bottom.

**Gregg et al. (2005) GRL, 32, L03606, doi:10.1029/2004GL021808**

**Behrenfeld et al. (2006) Nature doi:10.1038/nature05317**

# Nutrient and C inputs

## Belgian coastal zone (North Sea)

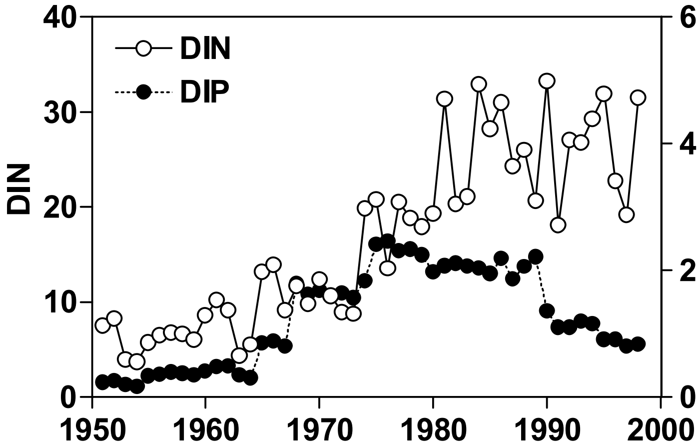



Lancelot et al. (2007) JMS 64:216-228
Gypens & Lancelot, Thursday 20th 09:30

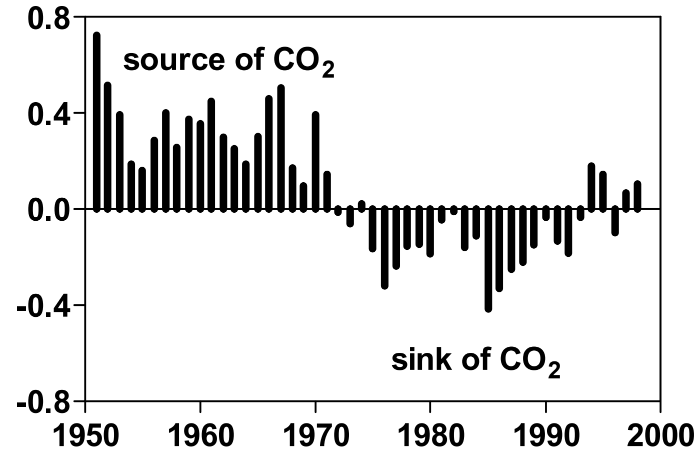
# Nutrient and C inputs

## Belgian coastal zone (North Sea)

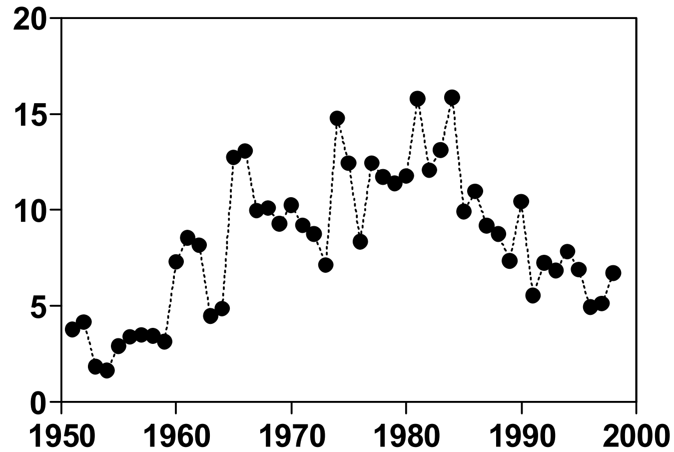
Nutrient inputs (kT $yr^{-1}$)



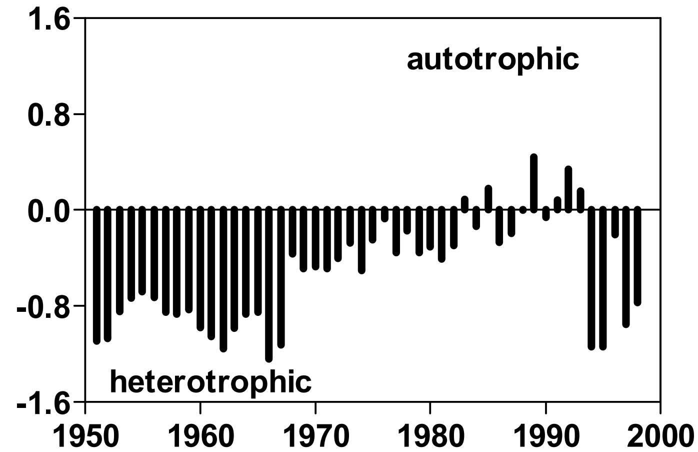

Air-sea $CO_2$ flux (mmol C $m^{-2}$ $yr^{-1}$)




Organic carbon inputs (T $yr^{-1}$)

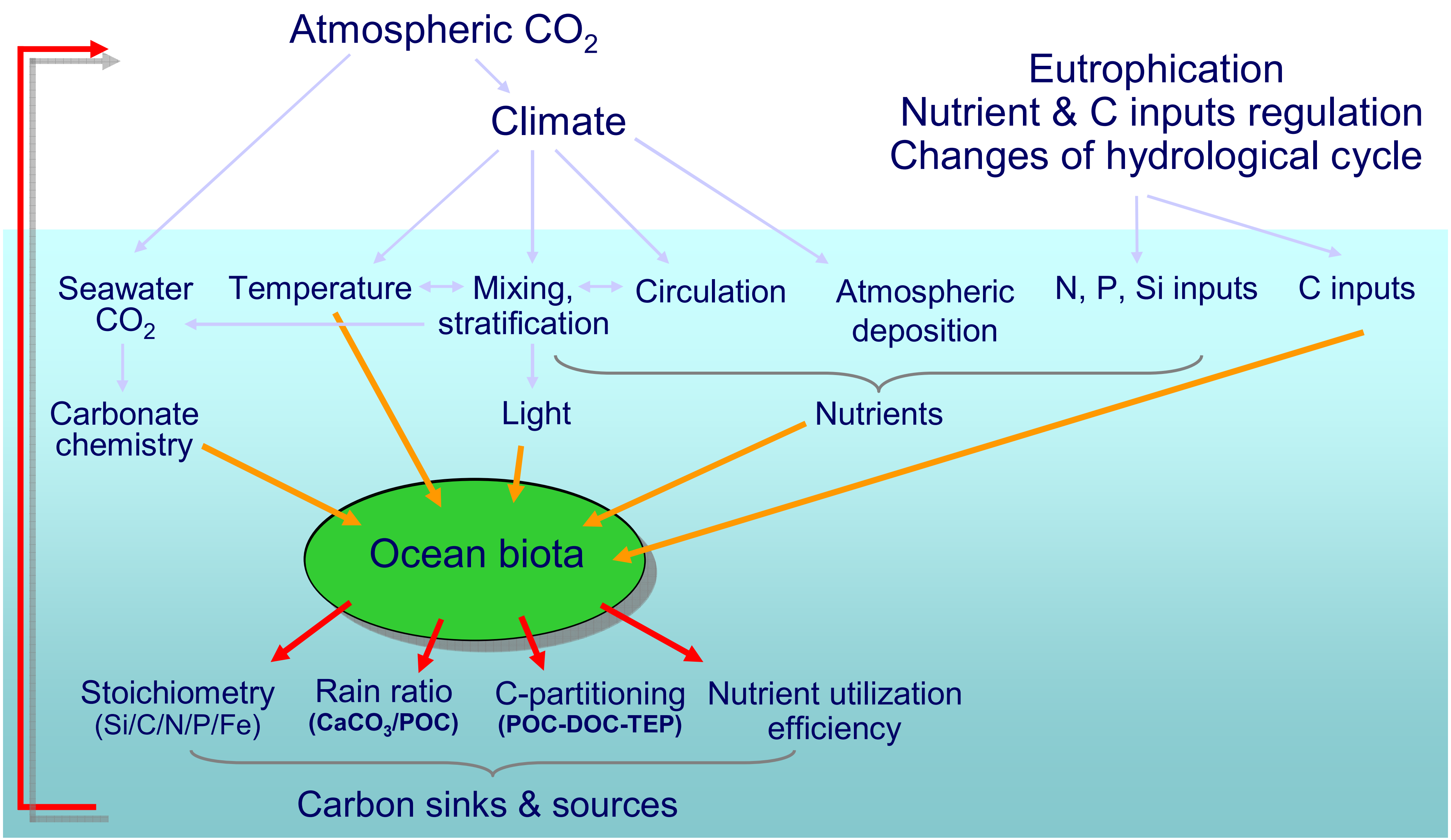



NEP (mmol C $m^{-2}$ $yr^{-1}$)

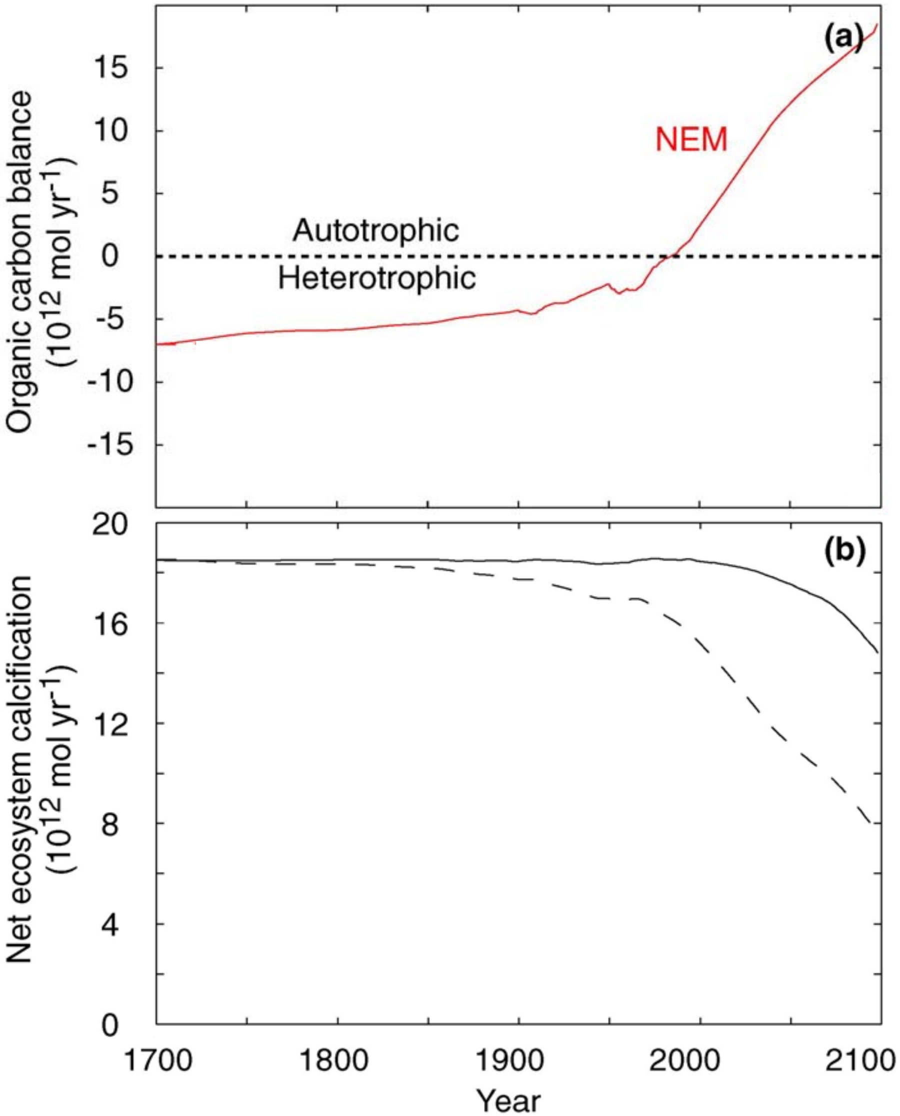



**Gypens & Lancelot (in prep.)**

# Summary ?


Atmospheric $CO_2$
Climate
Eutrophication
Nutrient & C inputs regulation
Changes of hydrological cycle
Seawater $CO_2$
Temperature
Mixing, stratification
Circulation
Atmospheric deposition
N, P, Si inputs
C inputs
Carbonate chemistry
Light
Nutrients
Ocean biota
Stoichiometry (Si/C/N/P/Fe)
Rain ratio ($CaCO_3$/POC)
C-partitioning (POC-DOC-TEP)
Nutrient utilization efficiency
Carbon sinks & sources

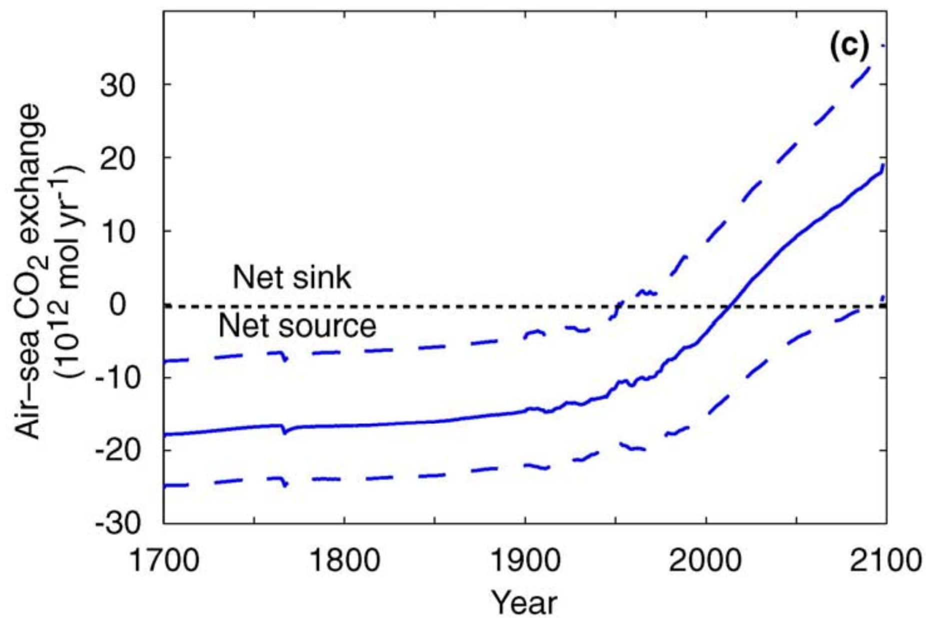
# Summary ?




**1 box model :**

**- Increase of $CO_2$ sink in the coastal ocean mainly due to net ecosystem metabolism (NEM) due to increase of nutrient delivery.**

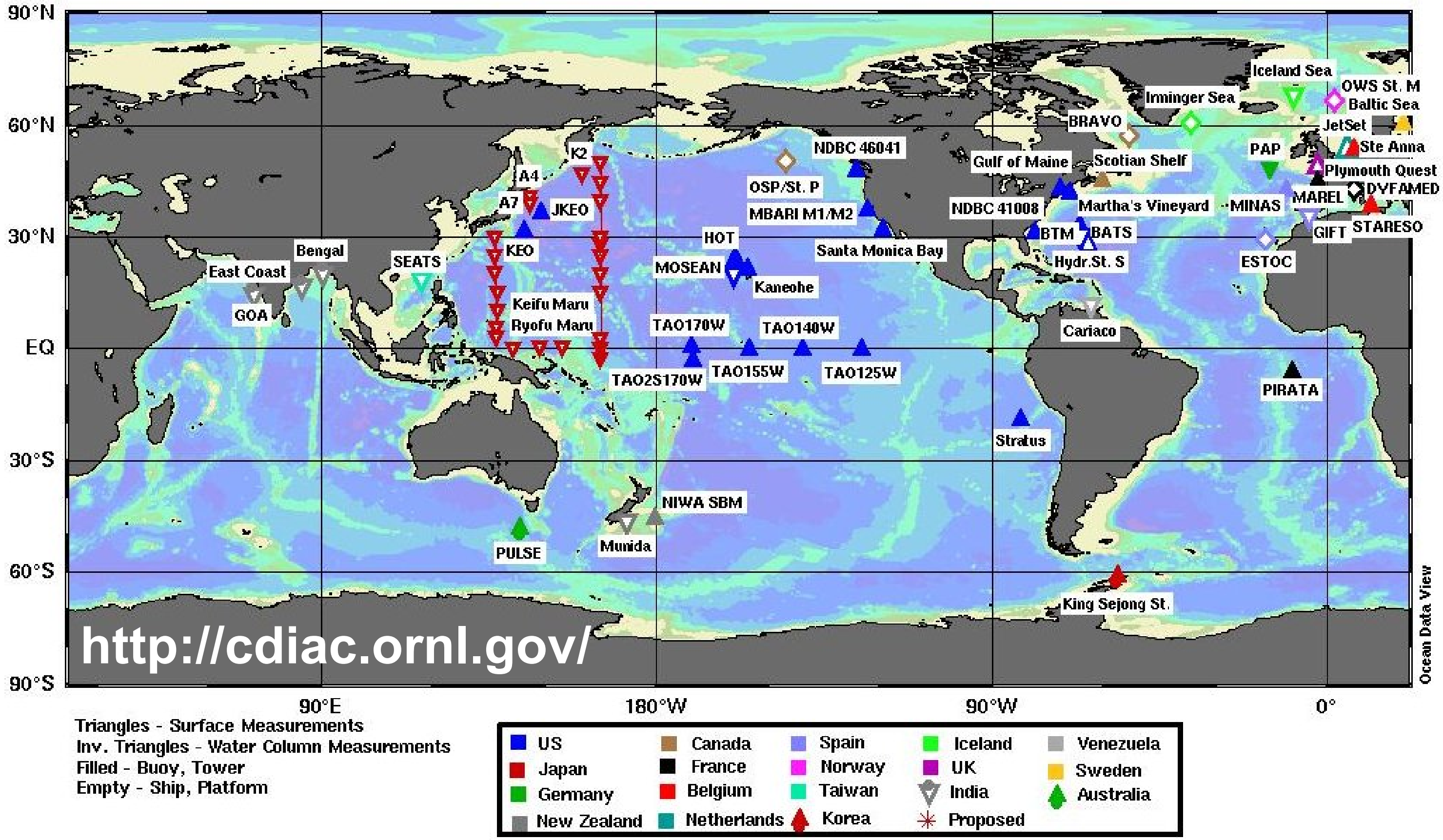
**- Decrease of calcification and increase of diagenetic $CaCO_3$ dissolution have a minor role.**




**Andersson & Mackenzie (2004) Front Ecol Environ 2: 348−353**
**Mackenzie et al. (2004) Biogeosciences 1:11−32**

# Ways forward ?

1. More $CO_2$ observatories (moorings, repeat tracks, repeat stations, …)




2. Adapted typologies for scaling $CO_2$ fluxes.

3. Several on-going 3D models (California current, North Sea, EU scale, North America scale …), but can we go global ?
(*i.e.* enough knowledge ? computing power ?)

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